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Mod-2 Wind Turbine System Development Final Report

Volume II—Detailed Report

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Boeing Engineering and Construction Company
(Division of The Boeing Company)

September 1982

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-2

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Wind Energy Technology Division

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1.0 PROJECT BACKGROUND

The MOD-2 Wind Turbine Program was initiated in August of 1977 when Boeing Engineering and Construction (a division of The Boeing Company) was awarded the contract for development of a multi-megawatt wind turbine system. This project was a continuation of the U.S. Department of Energy programs which had previously funded development of the experimental MOD-0 machine at the NASA LeRC Test Center at Plum Brook, Ohio; four of the 200 kW MOD-OA machines as installed and operated in New Mexico, Rhode Island, Puerto Rico, and Hawaii; and the 2000 kW MOD-1 machine installed in North Carolina. These earlier machines were invaluable in developing the technology required to harness the abundant and renewable energy from winds and provided a database for use in development of the MOD-2. The contract requirements established for the MOD-2 machine were structured to achieve a significant advancement towards early commercial realization of cost competitive electrical energy from wind power.

As with the earlier developmental programs, the NASA LeRC was assigned program and technical management responsibility for the MOD-2 machine.

1.1 PROJECT GOALS

Stated in general terms, the DOE/NASA goals for the MOD-2 program were as follows:

- o Provide an economically viable alternative electrical energy system (cost competitive with some conventional fueled power plants) which could reduce the dependency on non-renewable fossil fuel electrical generation systems.
- o Demonstrate feasibility of wind turbines operating in a utility network. The machine must be compatible with utility interface requirements and general utility operations and maintenance practices.
- o Stimulate wide industry involvement in the development of a commercial business base.

1.2 SPECIFIC DESIGN REQUIREMENTS

The primary design requirements established by the MOD-2 contract Statement of Work were:

(1) The machine shall produce multi-megawatts at rated power.

(2) The cost of electricity for the 100th production unit, when operated at a site with a mean wind speed of 14 mph, shall not exceed 4 cents per kilowatt-hour based on 1977 dollars.

(3) The machine shall be of the horizontal axis type.

(4) The rotor diameter shall be no less than 300 feet.

(5) The machine shall be compatible with integration into a utility network (including integration of multi-units in a farm concept).

(6) Design for safe and reliable operation over a period of 30 years.

(7) Design for unattended operation with automatic control for sequencing its operation.

The specific requirements as extracted from the contract Statement of Work are shown in Table 1-1.

1.3 DESIGN APPROACH

The generalized program approach was structured as illustrated in Figure 1-1. As shown, this was a phased program with several DOE and NASA reviews and approval prerequisites to entering the subsequent phase. In addition to the DOE/NASA review, several utilities were periodically briefed and contributed to the requirements for the interface to the grid, and the requirements for operations and maintenance (O&M).

The most significant phases in terms of establishing the configuration were the Concept and Preliminary Design Phases. A more detailed logic diagram leading to PDR is shown in Figure 1-2. Most significant in these activities are the trade studies which evaluated design and specification variations. The primary objective of all trade studies was to optimize system performance to obtain least cost of electricity. Table 1-2 summarizes the major studies leading to the preliminary design. The extensive analysis which led to the system definition at PDR is documented in reference 1. This final report focuses on the remainder of the program to the current O&M phase.

The Detail Design Phase developed the production design drawings and all procurement specifications. During this phase, competitive proposals were solicited and evaluated for the selection of major hardware suppliers. Long lead procurement of selected hardware was authorized by NASA prior to completion of the Detail Design Phase.

With NASA approval to enter the Fabrication Phase for three prototype machines, the remaining subcontracts were awarded for major components and procurement of all hardware was initiated. The major component suppliers for the MOD-2 program are shown in Table 1-3 and Figure 1-3. The major tasks in this phase were the release of the interface control drawings and specifications and the extensive subcontract management tasks to assure interface compatibility, quality, and schedule commitments were met. Integrated system testing of initial components was conducted prior to first rotation with the objective of design verification. Spares requirements for assembly and test were identified and unique wind turbine maintenance tools were designed and procured. Reliability and maintenance analyses were utilized to recommend an optimum operational spares provisioning to support the availability goals.

Failure Modes and Effects Analysis (FMEA) is noted in Figure 1-1 to be a continuing activity throughout the program. The purpose of these analyses is to assure that the machine will operate in a fully automatic unattended mode and provide for safe shutdown from any out-of-tolerance condition or single point failure. The FMEA is further discussed in Section 2.7.

Table 1-1. MOD-2 Requirements

REQUIREMENT/OBJECTIVE	VALUE
Design Requirements/Objectives	
Service Life	30 years
Power Output (3 phase, 60 Hz)	Megawatt range
Rotor Orientation	Horizontal axis
Weight and Dimensional (Transport)	Yes
Finish Duration	Yes
Cut-in/Rated/Cut-out Wind Speed	14/27.5/45 mph
Color and Identification Markings	Yes
Rotor Diameter	$\geq$ 300 feet
Environmental	
Mean Yearly Wind Speed at Site	14 mph at 30 feet
Wind Gradient	Varible Power Law
Wind Speed Frequency	Weibull
Gust Criteria	Yes
Altitude	0-7000 feet
Lightning Model	Yes
Seismic	Yes
Temperature Range	-40°F. to 120°F.
Other (rain, hail, snow, etc)	Yes
Maximum Design Wind	120 mph at 30 feet
Safety	
Fail Safe (Unattended)	Yes
Fire Detection	Yes
Site Security System	Yes
Hazard Protection	Yes
Network and Turbine Protection	Yes
Self Protection in Emergency	Yes
Obstruction Marking and Lighting	Yes
Operations & Maintenance	
Tools, Vehicles	Commercial
Automatic/Manual Operation	Yes
Availability Objective	.90 Minimum
Remote/Unattended Control	Yes
Data Systems Channels	> 100
Maintenance Concept	Yes
Cost	
Cost of Electricity (100th Unit)	Under 4¢/kWh ($1977)
Units in Farm	25
Production Rate	Yes
Fixed Charge Rate	.18
Cost of Elect. Equation Specified	Yes
Site Definition	Yes
Transport Distance	1,000 miles

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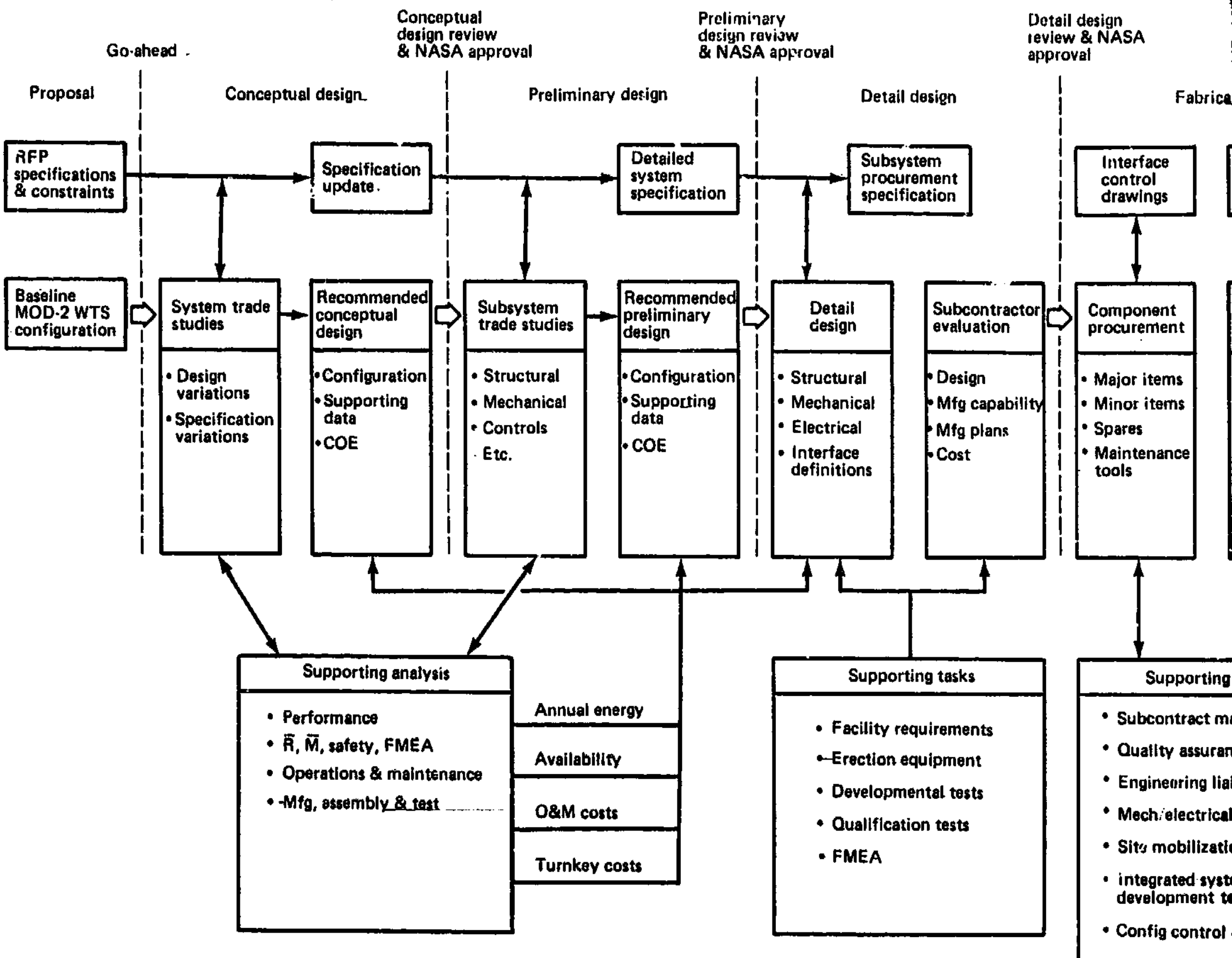

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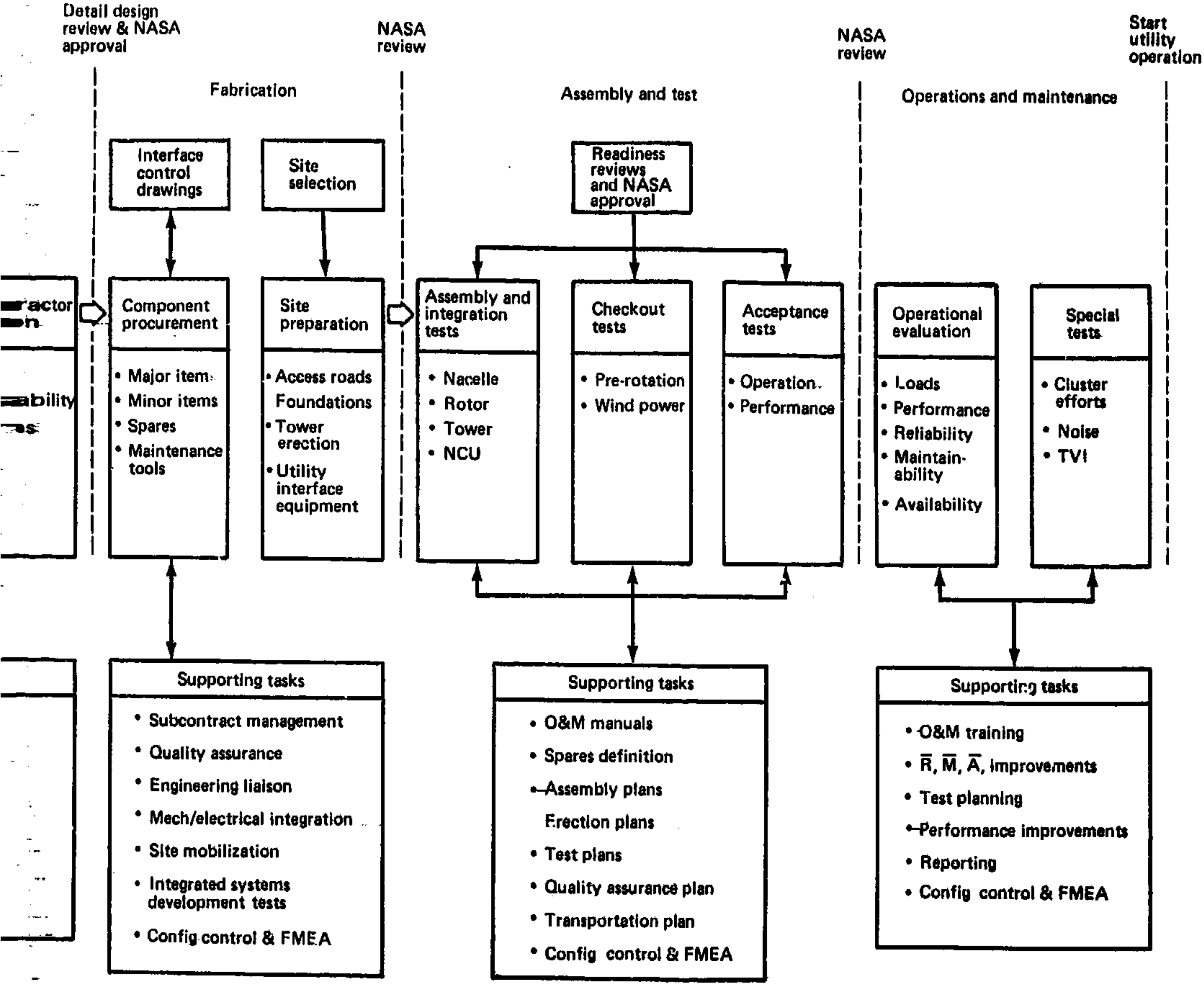

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Figure 1-1. Project Approach

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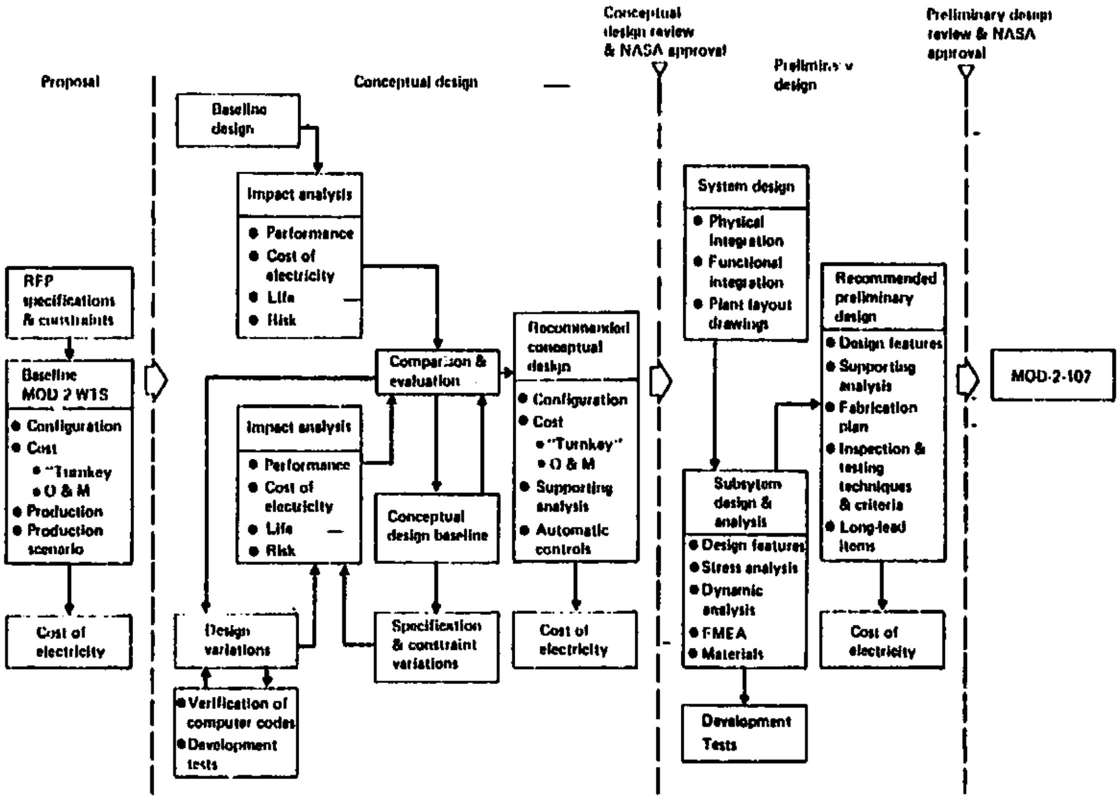

Figure 1-2. Wind Turbine Design Approach

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Table 1-2. Summary of Trade Studies (Sheet 1)

TRADE	SELECTED CONFIGURATION	REMARKS
Blade T.E. Configuration (welded steel plate vs. foam-filled fiberglass vs. steel skinned honeycomb panels & others)	Welded Steel Plate	Minimum cost and risk
Crack Detection System	Low Pressure flow through orifices	Cost effective means to provide early crack detection and WTS shutdown prior to failure
Crack Stopping Design	Not Practical	High risk structure
Metal vs. Composite Rotor	Metal rotor	Composite requires further development and is higher risk. Complicated pivot joint and hub to mid-blade joint
Upwind vs. Downwind Rotor	Upwind Rotor	Higher energy output reduces COE
Tip to Ground Clearance	50 feet	Larger values of ground clearance increased power output, but offset by increased system costs
Tilted vs Non-Tilted Rotor	No tilt	Small tilt angles can be accommodated if required for blade/tower clearance. Tilt above 4-5 degrees increases COE.
Epicyclic vs. Parallel Shaft Gear Box	Epicyclic Gearbox	Lower weight, lower cost, higher efficiency. COE reduced 0.55¢/kWh
Low Speed Shaft Support Configuration (Fixed vs. Inplane vs. Rotating)	Rotating Shaft support	Lowest risk, lightest weight, least COE
Generator Drive Selection (Direct vs. Gearbox Driven)	Gearbox Driven	Direct driven generator at 2500 kw would require 50 feet diameter pancake shape with $\leq$ 400 poles High weight & high cost
Power Generation (60 Hertz Direct vs. Static Inverter)	60 Hertz Direct (constant speed)	Static Inverter systems adds considerable cost. COE would increase 0.57¢/kWh
Generator Type Selection (Synchronous vs. Induction)	Synchronous Generator with soft quill shaft	Less risk, control understood COE reduced 0.035¢/kWh
Generator Speed Selection (1200 vs. 1800 rpm)	1800 rpm	Less generator cost, less drive train torque, gearbox not significantly costlier. Net COE reduction
Generator Voltage Selection (4.16 KV vs. 13.8 KV)	4.16 KV with transformer	Provides flexibility for multi-unit farm installations. 4.16 is standard for 2.5 mw generator. Smaller and lighter. Least system cost
Generator Selection (Effect of site altitude)	One design - standard commercial generator	Slightly derated at 7000 ft - hot day. Could accommodate extreme environment range with modified design at slight cost

Table 1-2. Summary of Trade Studies (Sheet 2)

TRADE	SELECTED CONFIGURATION	REMARKS
Fixed vs. variable speed rotor	Fixed speed rotor	Variable speed captures more energy but adds 0.57¢/kWh
Cut-in wind speed - low	14 MPH @ hub height	11 mph req'd to sustain rated rpm. 3 mph margin avoids frequent stop/start cycles
Cut-out wind speed - high	45 mph @ hub height	Total energy available above 45 mph is less than 1% for specified wind spectrum
Design Wind Speed	20 mph @ hub height	Maximum specific energy output for design specific power power rating of 35.4 watts/sq. ft.
Rated Wind Speed	27.5 mph @ hub height	Compatible with design wind speed
Design Power Rating	2500 KW generator	Considered minimum COE for specific power of 35.4 watts/sq. ft. in specified 14 mph wind spectra.
Design Service Life	30 years	Minimim COE considering periodic component replacements
Extreme Wind Speed	120 mph @ 30 ft.	Applicable for sites with highest occurrence of high winds such as Florida and Cape Hatteras. Negligible penalty at typical sites
Machine Size Optimization	2500 KW Generator 300 ft. dia. rotor	Considered minimum COE for site with 14 mph mean wind. See Figure 4.1.
Mean Wind Speed	Specification value = 14 mph	MOD-2 near optimum over typical site mean winds. See Figure 4.2
Two vs. Three Blade Rotor	Two blade rotor	Increased energy output of 3 blades more than offset by increased system costs.
Teetered vs. Rigid Rotor	Teetered rotor	Total WTS weight reduces 61,000 lb. COE reduced 0.14¢/kWh
Teeter Stop Study (Brake vs. rigid vs. spring vs. viscous damper)	Friction brake & rigid stop	Brake concept reduces risk and controls teetering when parked
Teeter Bearing Study (Roller vs. plain vs. elastomeric)	Elastomeric Bearing	Least complex, no lube system and seals required
Optimum Rotor Speed	17.5 rpm	Studies showed maximum energy output at 17.5 rpm. Higher rpm reduces system weight and cost, but not sufficiently to overcome energy loss.
Partial vs. Full Span Rotor Control	Partial (30% Tip)	Reduces loads, less complex hub, reduced weight, and COE reduces ≈ 0.4¢/kWh
Aluminum vs. Steel Tip Blade	Steel Tip Blade	Steel is negligibly heavier due to fatigue critical loads. Steel tip approx. $16,000 cheaper than aluminum. Eliminates development work on aluminum structure.
Airfoil Geometry (NASA 230XX vs. 430XX vs. 44XX and modifications)	NASA 230XX	For equal performance, the selected airfoil results in lightest rotor and least COE

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Table 1-2. Summary of Trade Studies (Sheet 3)

TRADE	SELECTED CONFIGURATION	REMARKS
Desirability of Emergency Deisel Driven Generator	No emergency generator	48 vdc - 50 amp-hour batteries handle requirements in the event of utility power loss
Generator Circuit Breaker (Nacelle vs. Ground Level)	Nacelle Located GCB	Eliminates additional yaw slip rings. Less complex, more reliable and least cost
Wiring Transfer Across Yaw Bearing (Slip ring vs flex cables)	Slip Ring	Nacelle rotation not limited. Flex cable would require development and test with high risk of limited life
Nacelle Yaw Drive (Electric vs. Hydraulic)	Hydraulic	Lower cost, smaller size, higher stall torque, may stall without damage
Nacelle Structural Concept (Truss vs. Heavy Bed Beam vs. Semi-Monocque)	Truss Type	Approximately 1/2 cost of other concepts. Slightly less weight
Nacelle Truss Members (Closed Box vs. Open I Section)	Open I Sections	Best weld capability, least fabrication cost
Tower Configuration (Soft shell vs. Stiff Truss)	Soft Shell Tower (freq = 1.3 - 1.5 cycles/rev)	Soft Tower attenuates 2/rev loads. Lighter, cheaper. COE reduces 1¢/kWh
Tower Configuration (Soft vs Soft-Soft Tower)	Soft shell tower	The soft-soft shell (0.8 cycles/rev) resulted in small diameter (7 ft) tower. Not adequate for man-lift and no appreciable cost saving
Tower Configuration (Braced vs. Conical Base)	Conical Base (250 inch diameter)	Braced tower structurally indeterminate. Susceptable to differential settlement. Higher risk with no significant cost saving
Tower Configuration (Cone to Cylinder transition, abrupt vs. hyperbolic)	Hyperbolic Transition	Hyperbolic reduces local stresses and eliminates approx. 3600 lb of ring and gussets
Control System (Analog vs Microprocessor)	Microprocessor-based Digital System	Reliability due to less parts, reduced cost, commercially available components, flexibility to accommodate system changes, superior performance
Control System - Microprocessor Location (Ground vs. Nacelle)	Nacelle Computer and Signal Conditioning	The ground located system requires multiplexing system. Nacelle location provides COE reduction of 0.1¢/kWh

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Table 1-3. Major Subcontractors

ITEM	SUBCONTRACTOR	FUNCTION
Rotor	Pittsburgh - Des Moines Steel Company	Fabrication
Tower	Chicago Bridge and Iron	Fabrication
Nacelle	Bucyrus-Erie, Inc.	Fabrication
Low Speed Shaft	Bucyrus-Erie, Inc.	Fabrication
Quill Shaft	E. M. Jorgensen Company	Forging and Machining
Shaft Coupling	SKF	Fabrication
Teeter Bearing	Lord Kinematics	Design and Fabrication
Gearbox	Stal-Laval	Design and Fabrication
Generator	Beloit Power Systems	Design and Fabrication
Gen. Acc. Unit	Golden Gate Switchboard Co.	Design and Fabrication
Bus Tie Contactor Unit	Golden Gate Switchboard Co.	Design and Fabrication
Slip Rings	Electro-Tec Corp.	Design and Fabrication
Yaw Bearing	Rotek	Design and Fabrication
Shaft Bearings	Torrington	Design and Fabrication
Assembly	BOECON	Construction

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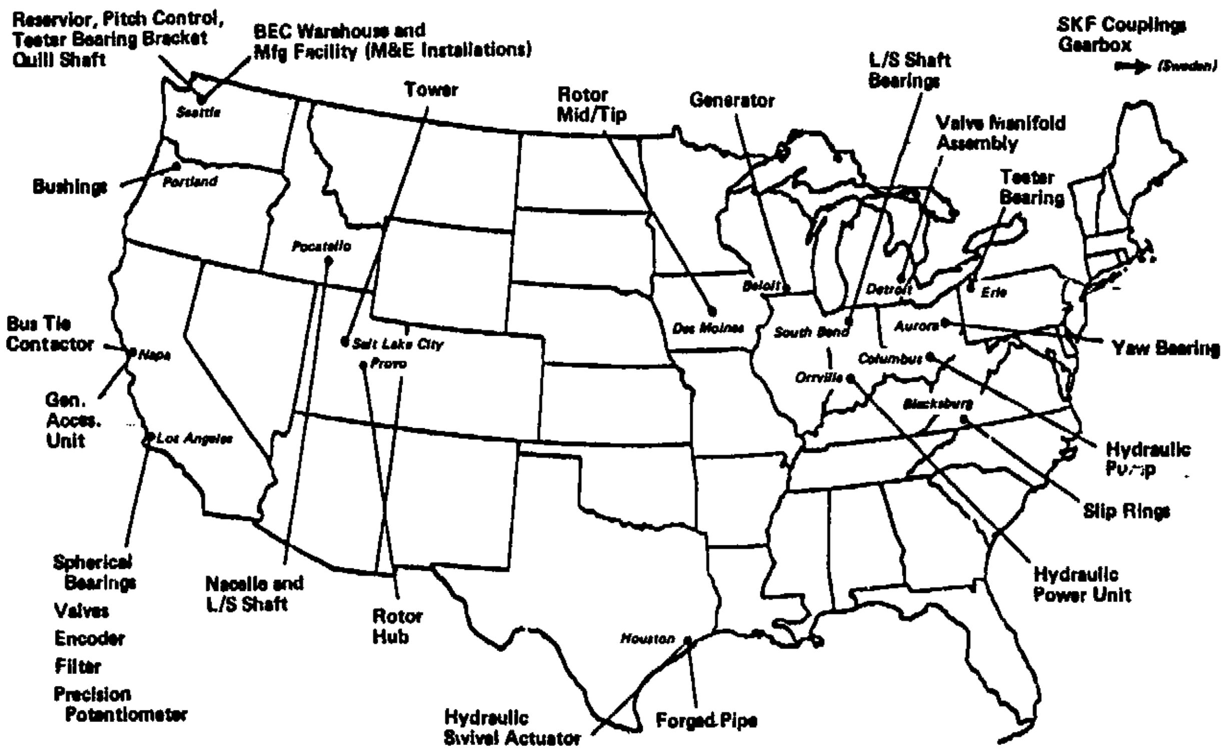

Figure 1-3. Major Supplier Locations

Following DOE evaluation of utility proposals, the Bonneville Power Administration (BPA) was chosen to be the operator of the three unit cluster of MOD-2 machines. The machines were to be installed at the BPA site located in the Goodnoe Hills near the Columbia River Gorge. This site is located near Goldendale, Washington and generated power is fed to the Klickitat County utility grid. Site layout plans were developed and 5, 7 and 10 diameter spacings between wind turbines established to support the evaluation of efficiency losses due to wake effects on multi-units in a cluster concept. Soil conditions were evaluated to enable foundation design. The site was mobilized under the direction of the Construction and Test Manager. Roads, laydown areas, foundations, underground power and communication interconnect, utility substation, and ground electrical facilities were installed. The towers were erected to support the arrival and installation of the wind turbine system. A detailed description of the site-preparation and wind turbine erection activity is provided in Appendix A.

The Assembly and Test Phase is described in Section 3.0 of this report. In summary, assembly and verification checkout of the nacelle and contents and of the rotor was first accomplished in the factory environment prior to partial disassembly for transporting to the site. The first MOD-2 unit underwent factory checkout with the nacelle and yaw bearing interfaced to a stub tower and interfaced to a rotor simulator. This allowed an evaluation of the pitch and yaw hydraulic actuated systems. After reassembly at the site functional checkout of all systems was conducted on the nacelle and rotor at the base of the tower. After satisfying all checkout test requirements, an installation readiness review was conducted and NASA approval obtained for installation. Following installation, a sequenced series of tests systematically led to the confidence to achieve wind powered operation and then synchronization and operation on the utility grid. This testing sequence is depicted in the test flow diagram of Figure 1-4.

The program is currently in the Operations and Maintenance phase. This O&M phase has been invaluable in providing engineering data to tune the system for reducing dynamic loads and improving system performance. Component reliability and system maintenance problems are being discovered, evaluated, and improvements incorporated. System availability is showing marked improvement as initial operational problems are being solved.

1.4 PROGRAM MASTER SCHEDULE

The chronology of significant program milestones as actually achieved is shown in Table 1-4. Original contract schedule milestones were achieved from contract award in August 1977 through the design phases to completion of detail design in May 1979.

There were five particularly significant events during the subsequent contract performance period which led to major program phasing changes. These were:

(1) Site selection and site access delay (1979)

(2) Rotor fabrication slides (mid 1980)

(3) Boilermaker union strike (1980-1981)

(4) Winter weather and low winds (1980-1981)

(5) Major equipment failure of WTS No. 1 (1981)

The spectrum of potential problems is evident in these events. The access to the site for initial preparation of facilities, soil tests for foundation design, roads, foundation installation, etc., was nearly nine months later than originally scheduled. The difficulty in forming, fabricating, and heat treating the large rotor structures resulted in a six-month slide from March to September 1980 for delivery of the final blade section. Work at the site was well underway when the boilermaker's union struck in nine western states in October 1980. All work at sites #2 and #3 was stopped for six weeks and picketing held up work on site #1 for two weeks. When finally settled, it was late November and adverse weather severely slowed work in the field. Although WTS #1 achieved initial rotation the morning of November 1, much of November 1980 to May 1981 was lost due to poor weather and below normal winds.

On June 8, 1981, during a planned emergency shutdown test, a pitch system valve malfunction resulted in an overspeed condition to WTS #1. The overspeed destroyed the generator and quill shaft and caused minor damage to several smaller components. All operations on WTS #2 and #3 were suspended for five months while damage assessments, failure investigations and system design changes were implemented. Operations and testing of WTS #2 and #3 were resumed in October 1981 under controlled conditions. WTS #1 returned to operation in April, 1982.

The program schedule achieved is shown in Figure 1-5.

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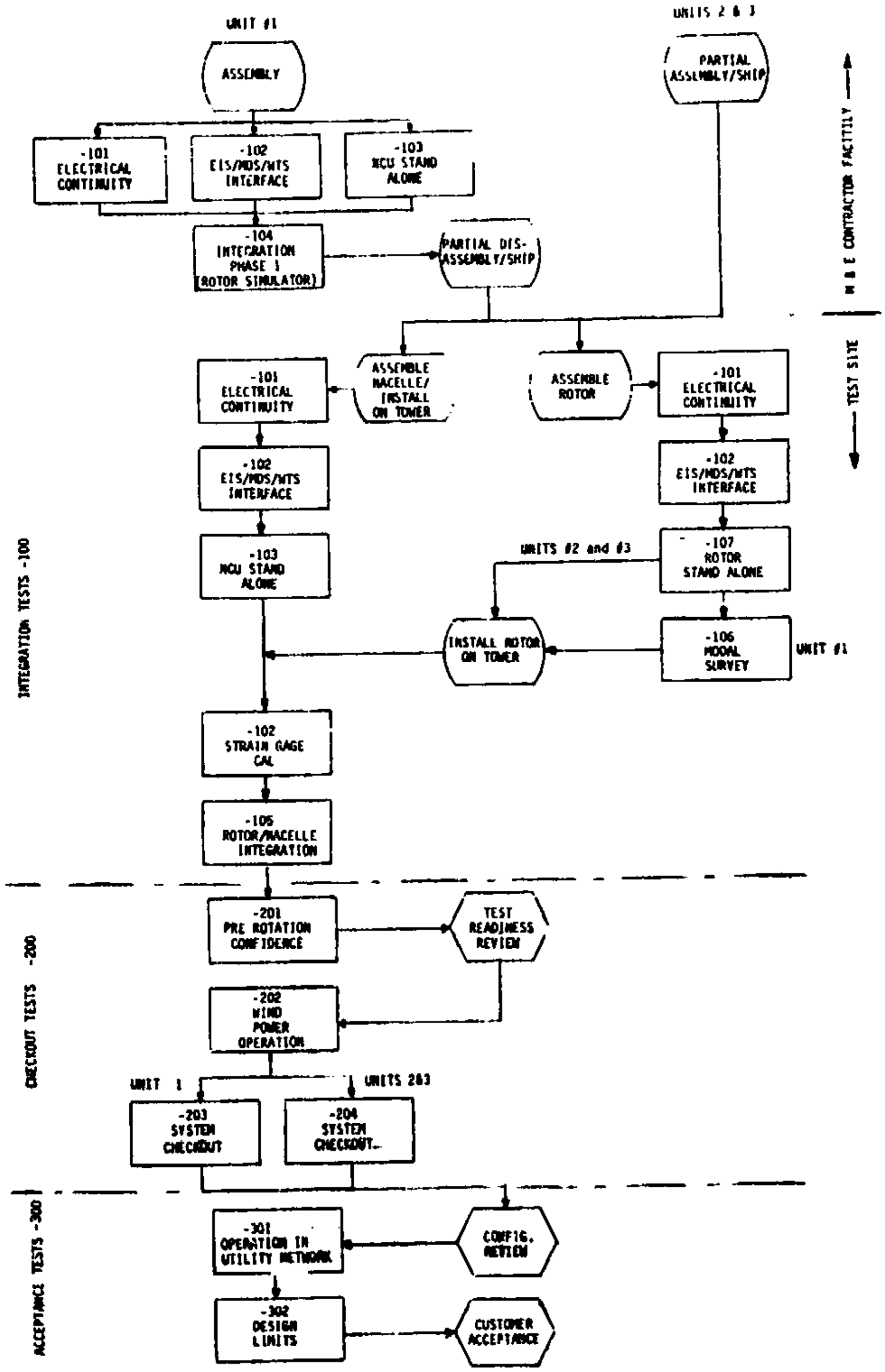

Figure 1-4. System Test Flow

Table 1-4. Significant Program Milestones

GO-AHEAD	AUG 1977
CONCEPTUAL DESIGN COMPLETE	JUL 1978
PRELIMINARY DESIGN COMPLETE	NOV 1978
DETAIL DESIGN COMPLETE	MAY 1979
FABRICATION START	JUN 1979
DOE SITE SELECTION	OCT 1979
1ST UNIT SCHEDULE	
START SITE PREPARATION	MAR 1980
SITE PREPARATION COMPLETE	JUN 1980
COMPONENT FABRICATION COMPLETE (LESS ROTOR)	JUL 1980
TOWER INSTALLATION COMPLETE	AUG 1980
NACELLE INTEGRATION AND TESTS COMPLETE	AUG 1980
ROTOR FABRICATION COMPLETE	SEP 1980
SITE INSTALLATION COMPLETE	OCT 1980
INITIAL ROTATION	NOV 1980
1ST UNIT CHECKOUT COMPLETE	FEB 1981
2ND UNIT CHECKOUT COMPLETE	MAY 1981
DEDICATION OF SITE	MAY 1981
3RD UNIT CHECKOUT COMPLETE	JUN 1981
1ST UNIT OVERSPEED INCIDENT	JUN 1981
WIND TURBINE OPERATION STOPPED	JUN 1981
INCIDENT INVESTIGATION COMPLETE	SEP 1981
RESUME OPERATION UNIT 3	OCT 1981
RESUME OPERATION UNIT 2	OCT 1981
RESUME OPERATION UNIT 1	APR 1982
TECHNICAL ACCEPTANCE	MAY 1982
FINAL ACCEPTANCE	OCT 1982

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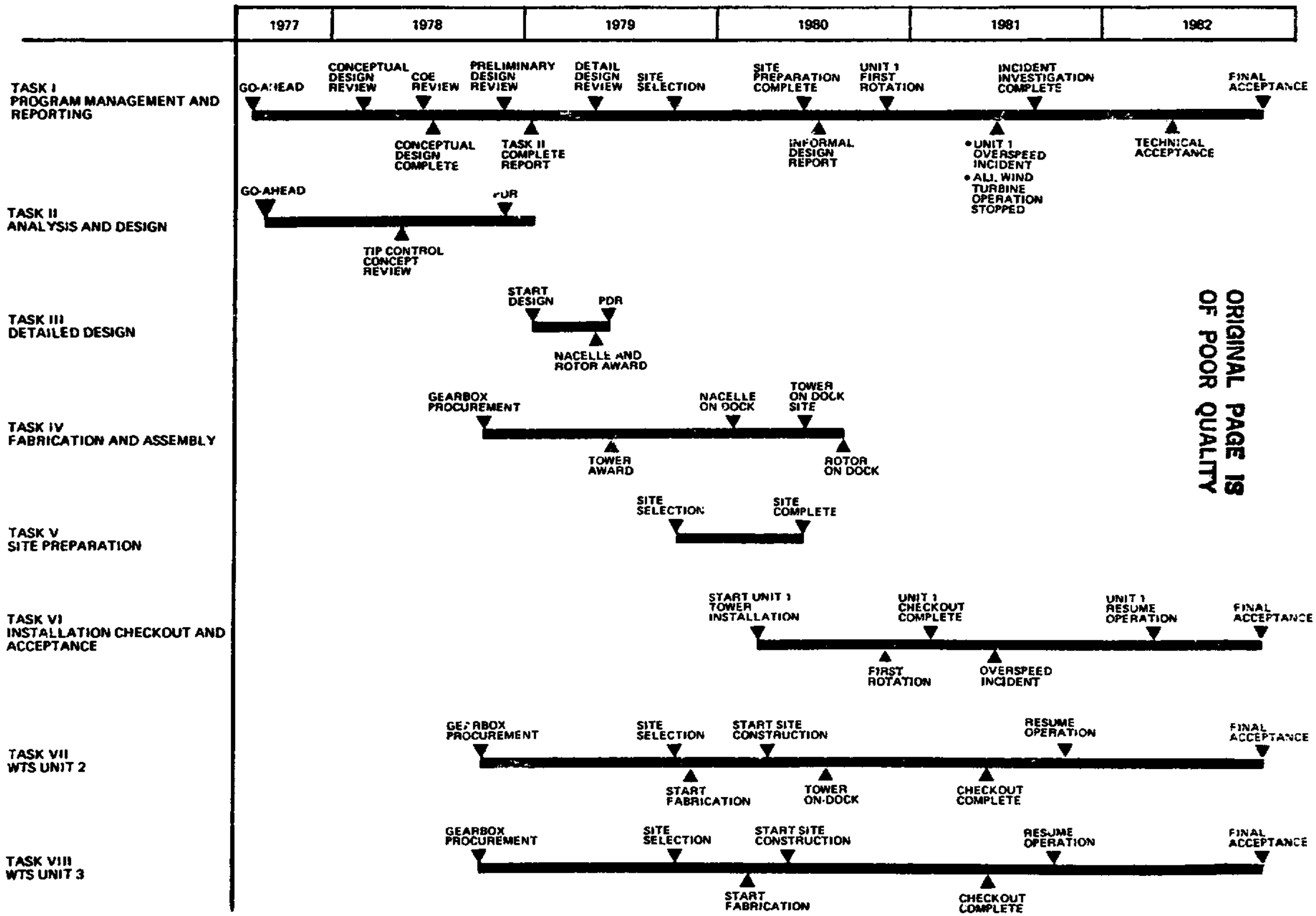

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Figure 1-5. As Completed MOD-2 Contract Schedule

2.0 SYSTEM DESCRIPTION

This section describes the MOD-2 Wind Turbine System (WTS) now operating in the 3 unit cluster near Goldendale, Washington. It is essentially identical to the configuration described in reference 1 with minor system modifications resulting from the test phase experience.

2.1 GENERAL ARRANGEMENT AND CHARACTERISTICS

A photo of a MOD-2 at Goldendale is shown in Figure 2-1. The general arrangement and characteristics of the current WTS configuration are shown in Figure 2-2. It is designed for operation at sites where the annual average wind speed is 14 mph measured at 30 feet (20 mph @ hub height). The system generates electricity when the wind speed at hub height (200 feet) exceeds 14 mph. At 27.5 mph and higher (at hub height), the system is designed to produce its rated power of 2500 kW. Above 45 mph (at hub height), the system is shut down to avoid high operating load conditions. The annual energy output at a site with a 14 mph average wind speed @ 30 ft. is 9753 million kWh. This energy output combined with an estimated 100th production unit turnkey cost of $2,109,000 (in 1980 dollars) results in a predicted cost of electricity of 4.1¢/kWh at the bus bar. During operation, the wind turbine is tied to the utilities power grid through standard transmission lines.

The WTS is a horizontal axis machine utilizing a 300 foot diameter partial span control, upwind rotor. The rotor's center of rotation is 200 feet above ground level. It is coupled to the low speed shaft through an elastomeric teeter bearing. A 2500 kW synchronous generator is driven via a step-up planetary gearbox and "soft" quill shaft. The generator, gearbox, hydraulic systems, electronic controls and other support equipment are enclosed in a nacelle mounted atop a cylindrical steel tower. The nacelle can be yawed (rotated) to keep the rotor oriented correctly into the wind as the wind direction changes. A hydraulic pitch control system is used to control the position of the movable rotor tips. The movable rotor tips are used to obtain a constant rotational speed of 17.5 rpm, and to maintain the proper power output at wind speeds above rated wind speed (27.5 mph @ hub).

The WTS is controlled by an electronic microprocessor. The microprocessor is designed to allow unattended operation of the WTS at a remote site by monitoring wind conditions and the operational status of the wind turbine. Equipment failures result in automatic safe shutdown of the WTS. System status is monitored at the utility substation, from which maintenance crews are dispatched as needed.

2.2 SUBSYSTEM DESIGN

This section describes the basic subsystems and major components of the wind turbine. It is divided into rotor, drive train, nacelle, tower/foundation, electronic control and electrical power system sections.

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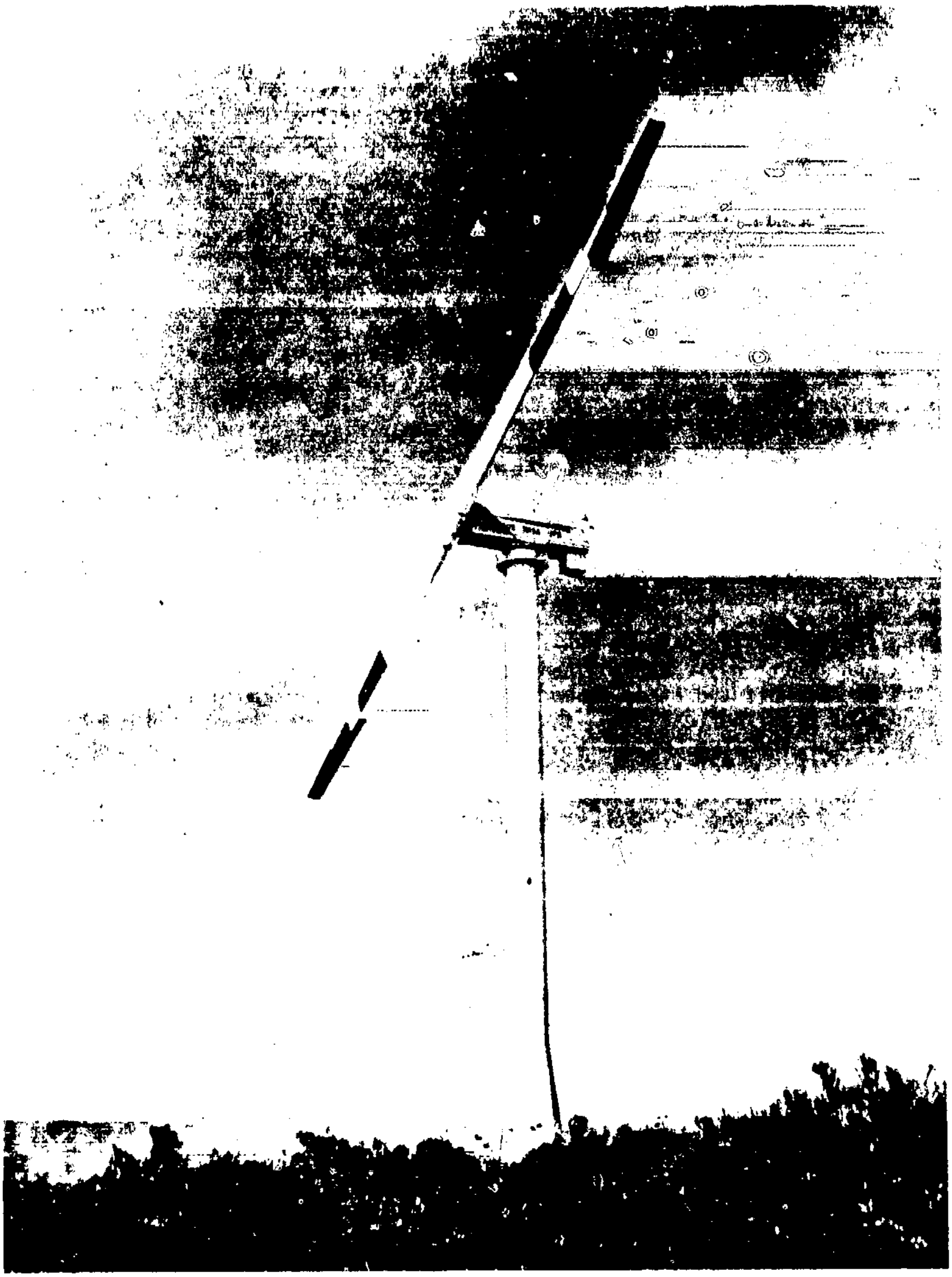

Figure 2-1. Goldendale WTS Number 1

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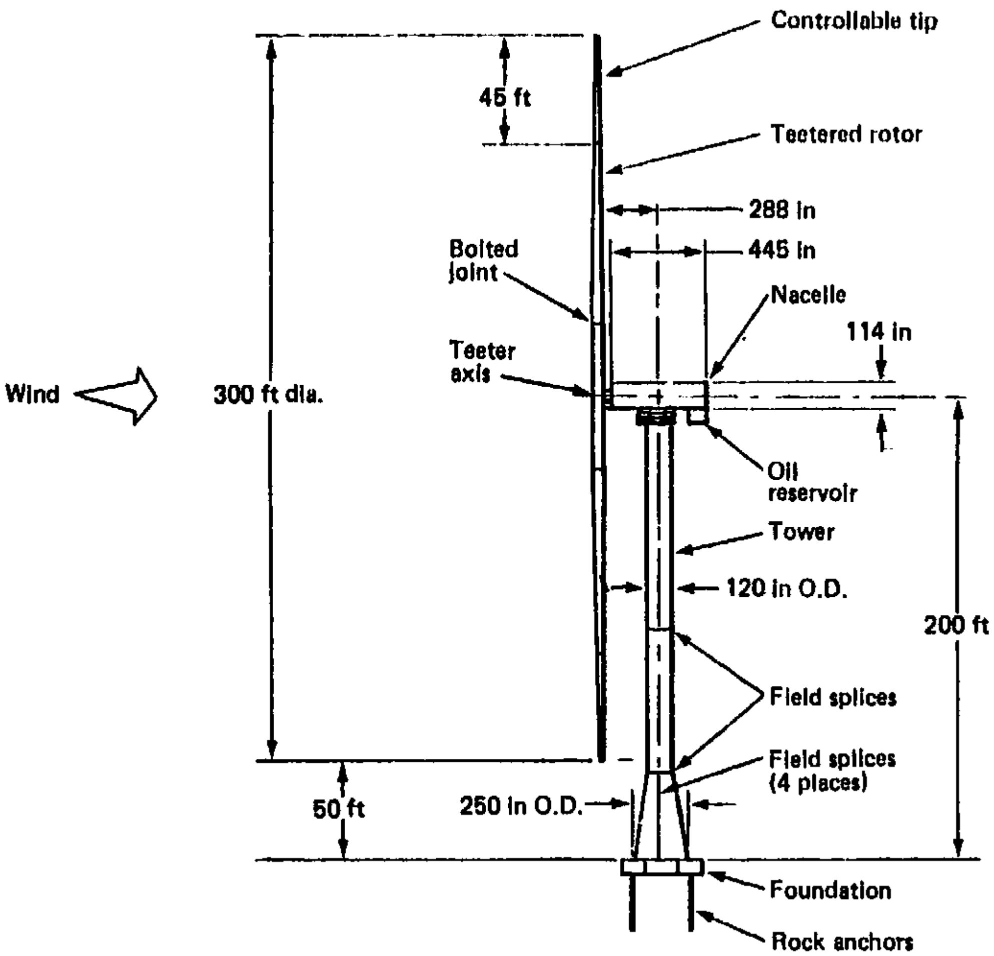

Rated power	2,500 KW
Rotor diameter	300 ft
Rotor type	Teetered - tip control
Rotor orientation	Upwind - 2.5° tilt
Rotor airfoil	NACA 230XX
Rated wind @ hub	27.5 mph
Cut-off wind speed @ hub	45 mph
Rotor tip speed	275 ft/sec
Rotor rpm	17.5
Generator rpm	1,800
Generator type	Synchronous
Gear box	Compact planetary gear
Hub height	200 ft
Tower	Soft-shell type
Pitch control	Hydraulic
Yaw control	Hydraulic
Electronic control	Microprocessor
System power coefficient (max)	0.382

Figure 2-2. Configuration Features and Characteristics

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2.2.1 Rotor

The MOD-2 WTS has a steel, two bladed, teetering, tip control type rotor with continuous carry through structure at the hub. It utilizes a NACA 230XX series airfoil rotating at 17.5 rpm (275 ft/sec tip speed). The basic construction is a welded steel shell with steel spar members.

As shown in Figure 2-3, the rotor is divided into three primary sections; the tip, the mid section, and the hub section. The tip (outer 30%) is rotated with respect to the remainder of the blade to control rotor speed and power. The tip and mid sections are the working portions of the blade. The hub section is attached to the mid section with a field splice and is a transition from an airfoil cross-section to an oval cross-section.

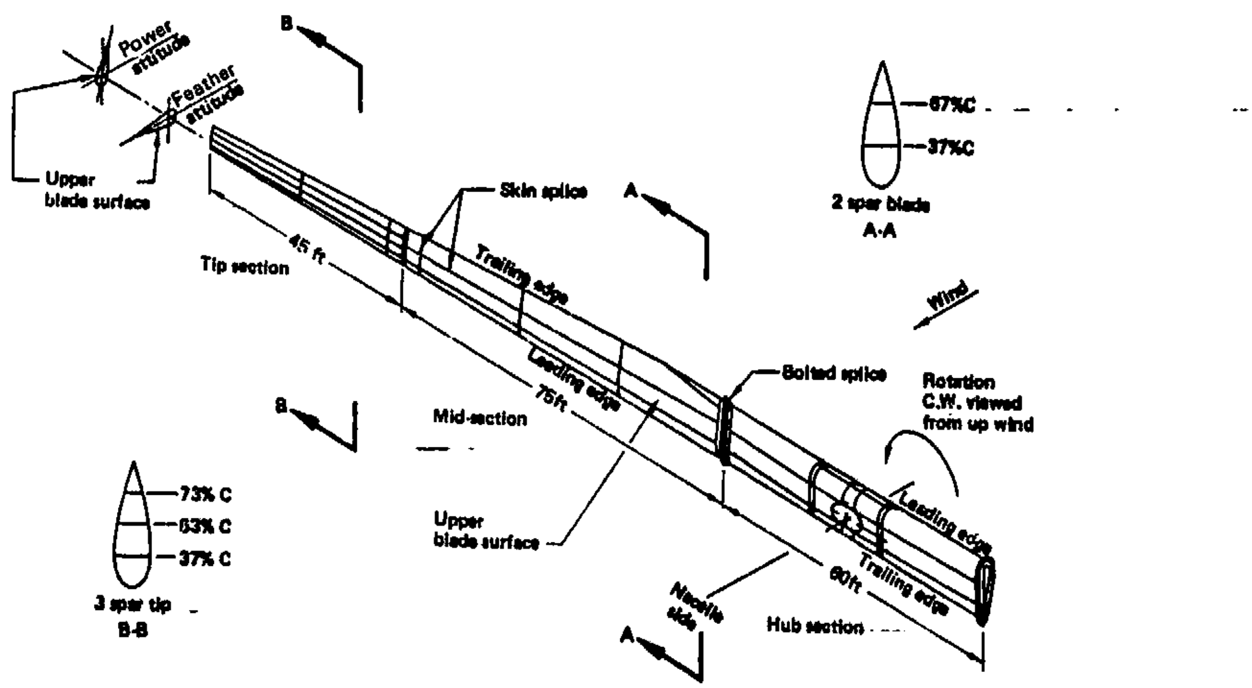

Figure 2-3. Rotor Configuration

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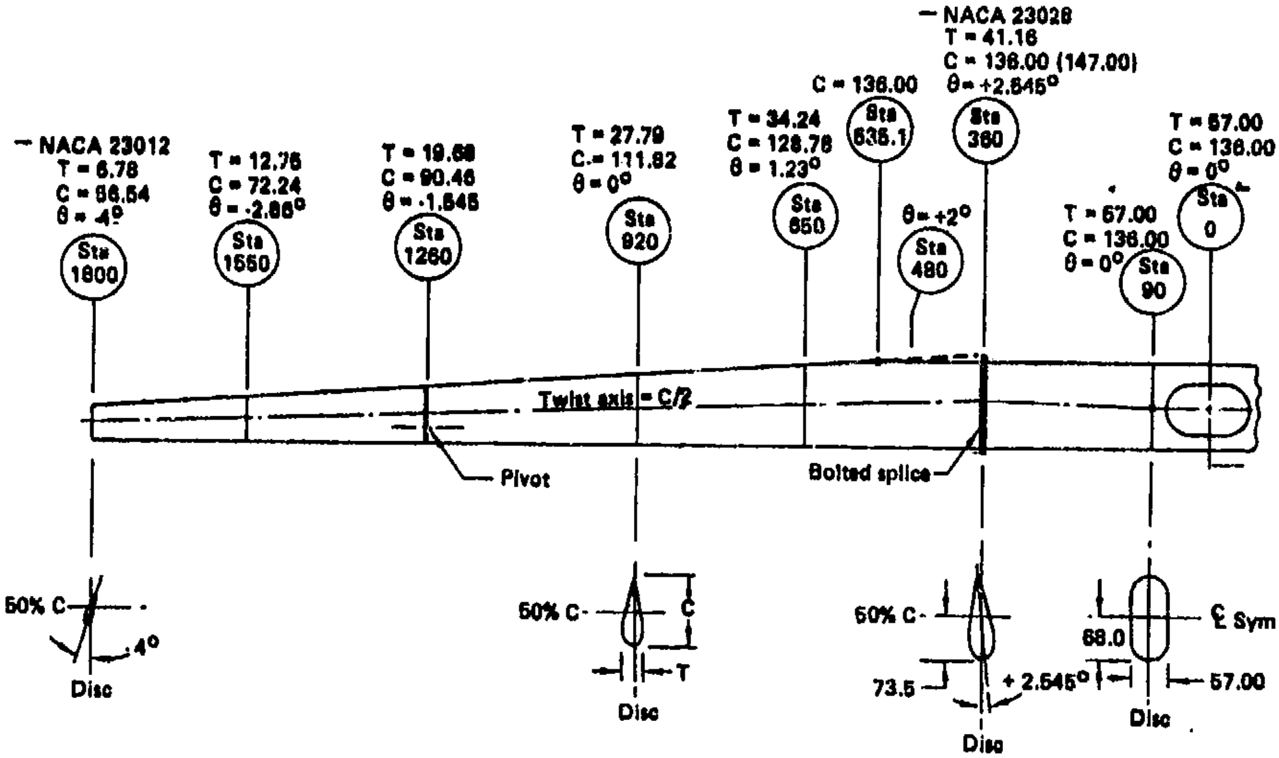

Figure 2-3A. Steel Rotor Design Details

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The rotor was fabricated from ASTM A633 steel by Pittsburg-Des Moines Steel Company at plants located in Ogden, Utah and Des Moine, Iowa. Sections of the rotor during fabrication are shown in Figure 2-4.

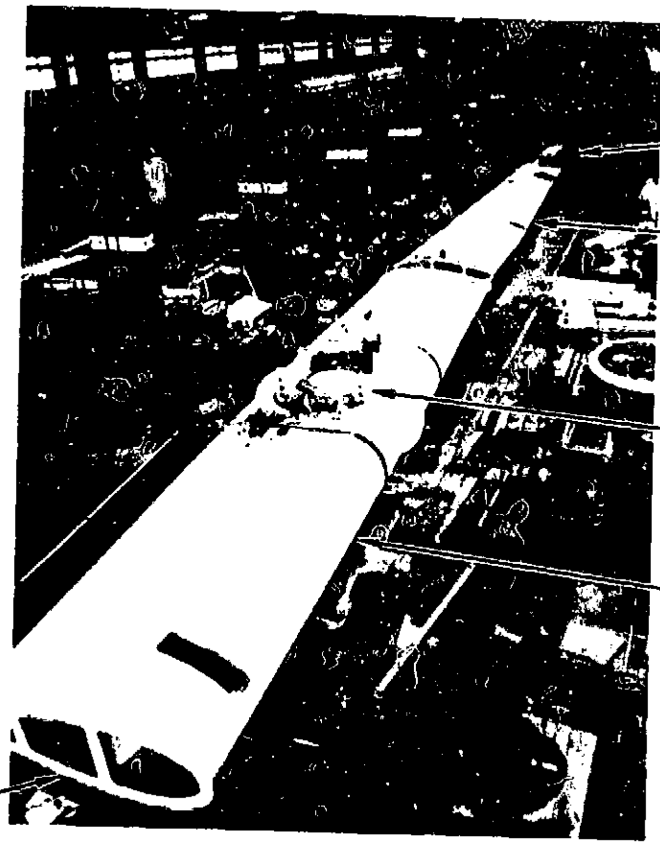

Figure 2-4. Rotor Assembly

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Each tip is controlled by a hydraulic actuator mounted on the blade mid section adjacent to the tip section as shown in Figure 2-5. The flow control to the actuators is governed by a signal from the automatic control system to servo valves. The position of the tips is monitored by position transducers and fed back to the control system. The normal rate of rotation of blade tips is from 0.1 to 1 degree per second.

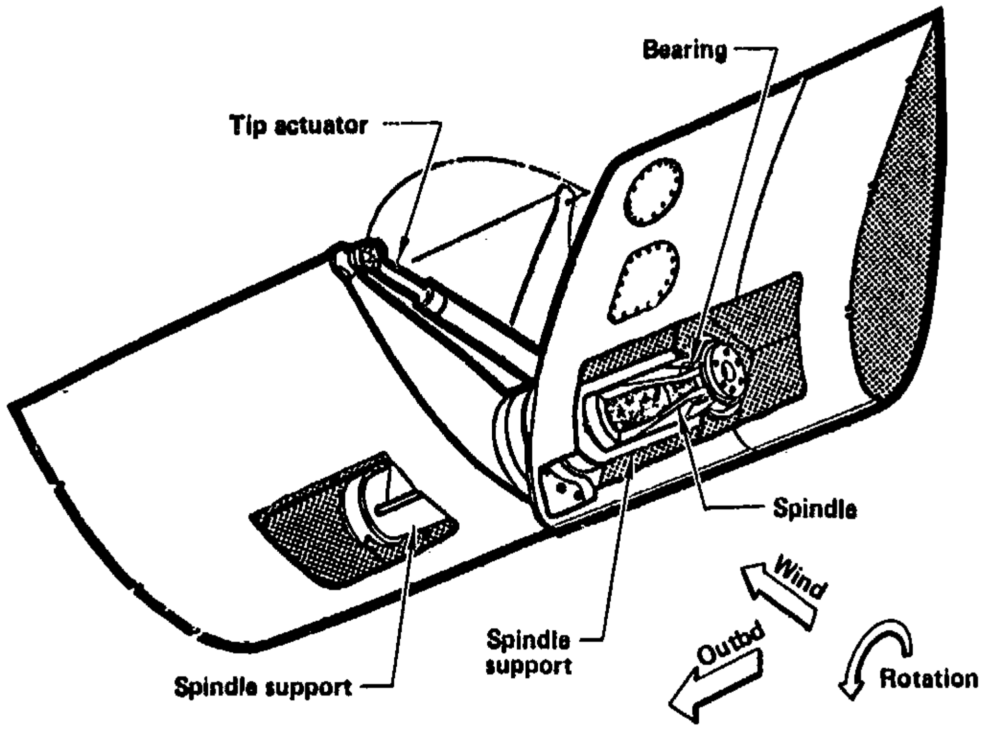

Figure 2-5. Tip Spindle Installation

In the event of critical system faults, the actuators drive the blade tips to the feathered position at rates of 4 to 8 degrees per second (depending on actuator position), using energy stored in separate hydraulic accumulators. The pitch rates are such that under any failure mode, no overspeed will exceed 15% of normal rpm. Redundancy is provided by the ability of either one of the operating actuators to shut down the system should one actuator become inoperative. Locks are provided to hold the blade tips in the feathered position when the hydraulic system is depressurized.

The blade tip section with the spindle assembly and the hydraulic actuator are attached to the blade mid section as a unit (Figure 2-5). The attachment is made by 6 bolts for ease of assembly and removal. Either blade tip can be removed independently from the WTS. The spindle protrudes into the blade mid section in a way which provides a load path for centrifugal and bending moments. Tapered rings at the outboard rib and a close tolerance bushing at the inboard rib assure a tight fit between the spindle sleeve and the mid section of the rotor. The bearings are lubricated with a long-life grease.

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The pitch control hydraulic system consists of an electrical motor driven pump, reservoir, accumulators, filters, heat exchangers, control valves, associated plumbing and actuators. Hydraulic components not located in the blade are installed on and rotate with, the low speed shaft (Figure 2-6). This eliminates any requirement for a hydraulic slip ring.

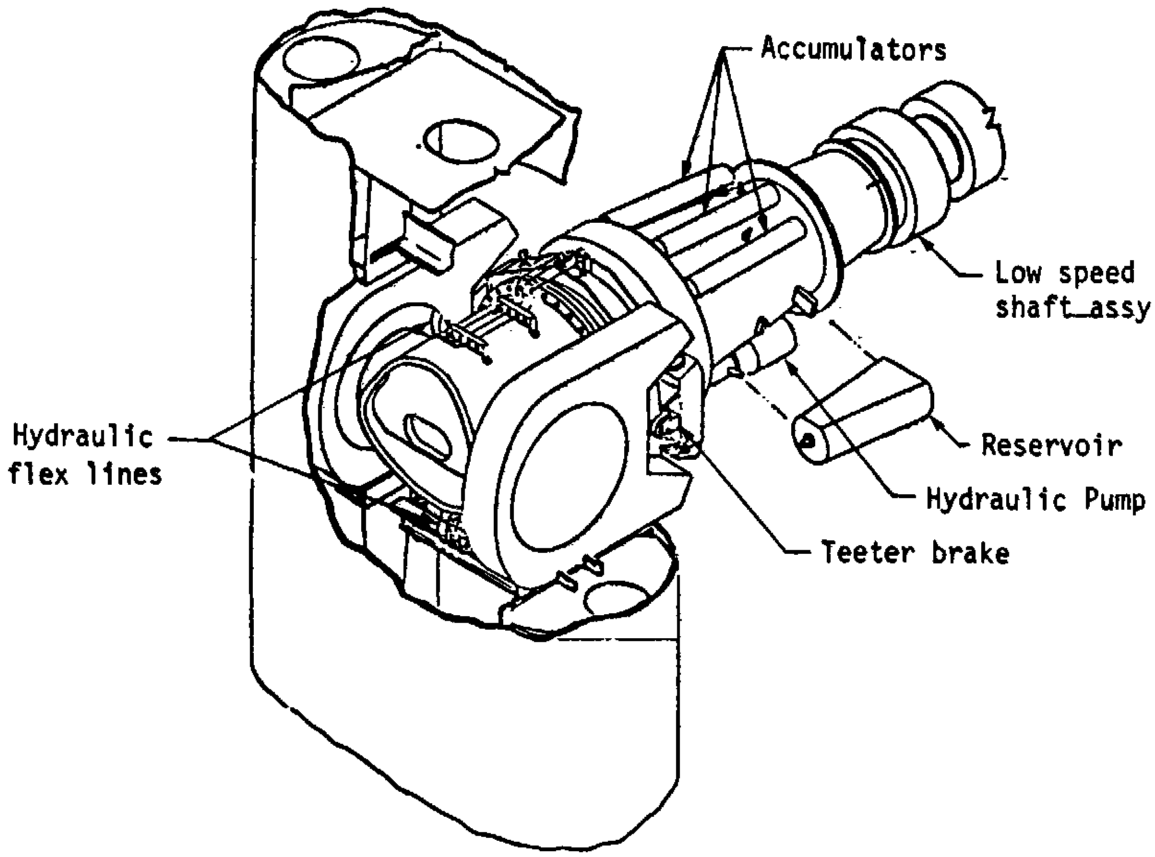

Figure 2-6. Pitch Control Hydraulics

Because the hydraulic system is located in a rotating environment, special attention has been applied to design for this environment. The components on the low speed shaft are exposed to approximately 1.3 g's and the reservoir has been tested in this environment with no adverse effects. The blade tip control actuator, rotating in an 11 g environment, has been selected with oversize rod and piston bearings, and is in the retracted position when exposed to this environment.

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The attachment of the rotor to the low speed shaft is by a teeter type bearing, which minimizes the one per revolution blade flapwise loads and the effects of small unsymmetric gusts, resulting in reduced fatigue loads. The teeter motion takes place in two radial elastomeric bearings which also transmit the rotor output torque into the rotor (low speed) shaft (Figure 2-7). The use of the elastomeric bearings eliminates lubrication requirements and prevents fretting that would be likely to occur if roller bearings were used. The elastomeric bearings consist of concentric alternate layers of sheet steel and rubber bonded together forming a package that is highly flexible in torsion and provides the required radial load capabiltiy.

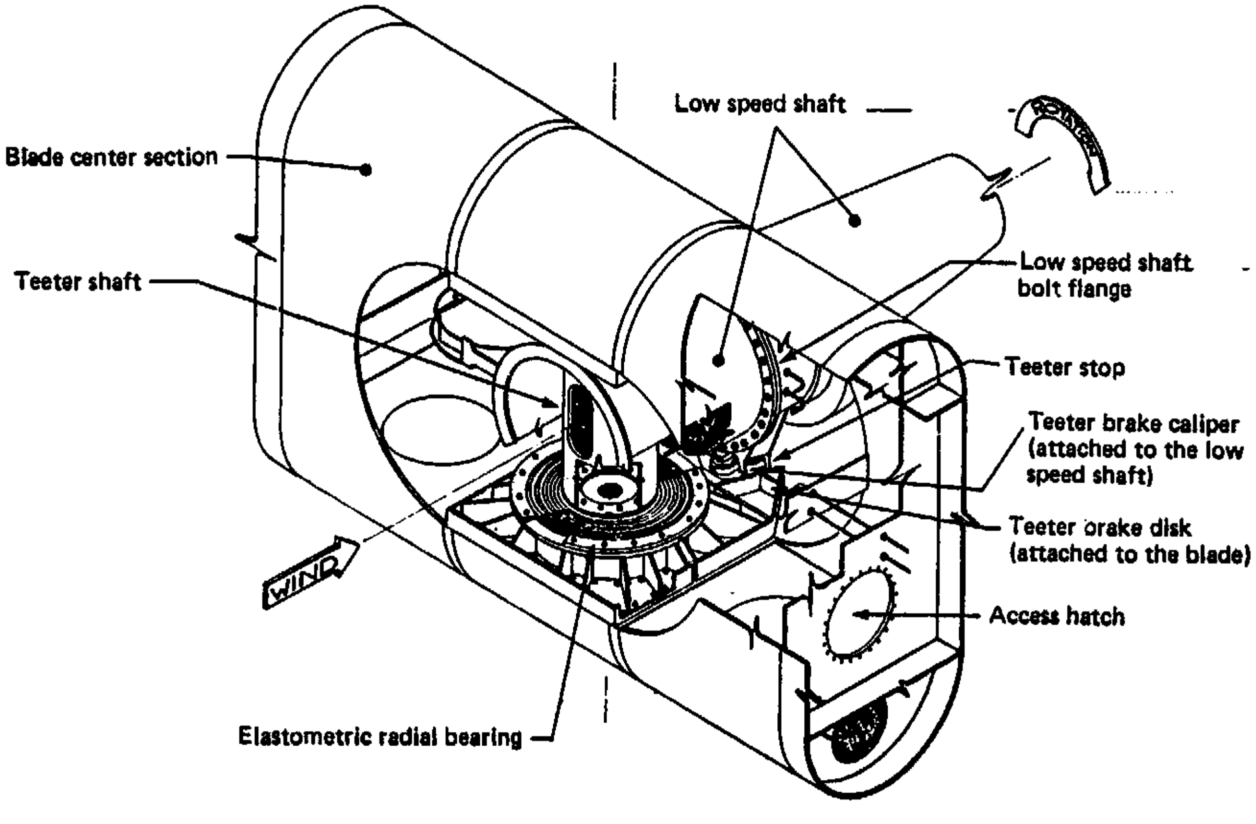

Figure 2-7. Teeter Bearing Installation

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Stops are provided to limit teeter motion to ±6.5°. A teeter brake was provided to prevent rocking when the rotor is in the standby mode, and to dampen teeter excursions during starting and stopping. Subsequent tests have shown that the teeter brake is not required, and therefore, the brake has been disconnected. During erection, the rotor, with teeter bearings and upwind end of the low speed shaft installed, can be lifted in one piece and bolted in place at the low speed shaft bolt flange using 32 bolts.

The teeter bearing is fabricated by Lord-Kinematics in Erie Pennsylvania. Figure 2-8 shows the bearing during cyclic load testing in the Boeing test facility. A detailed description of this test is provided in paragraph 3.1.5.

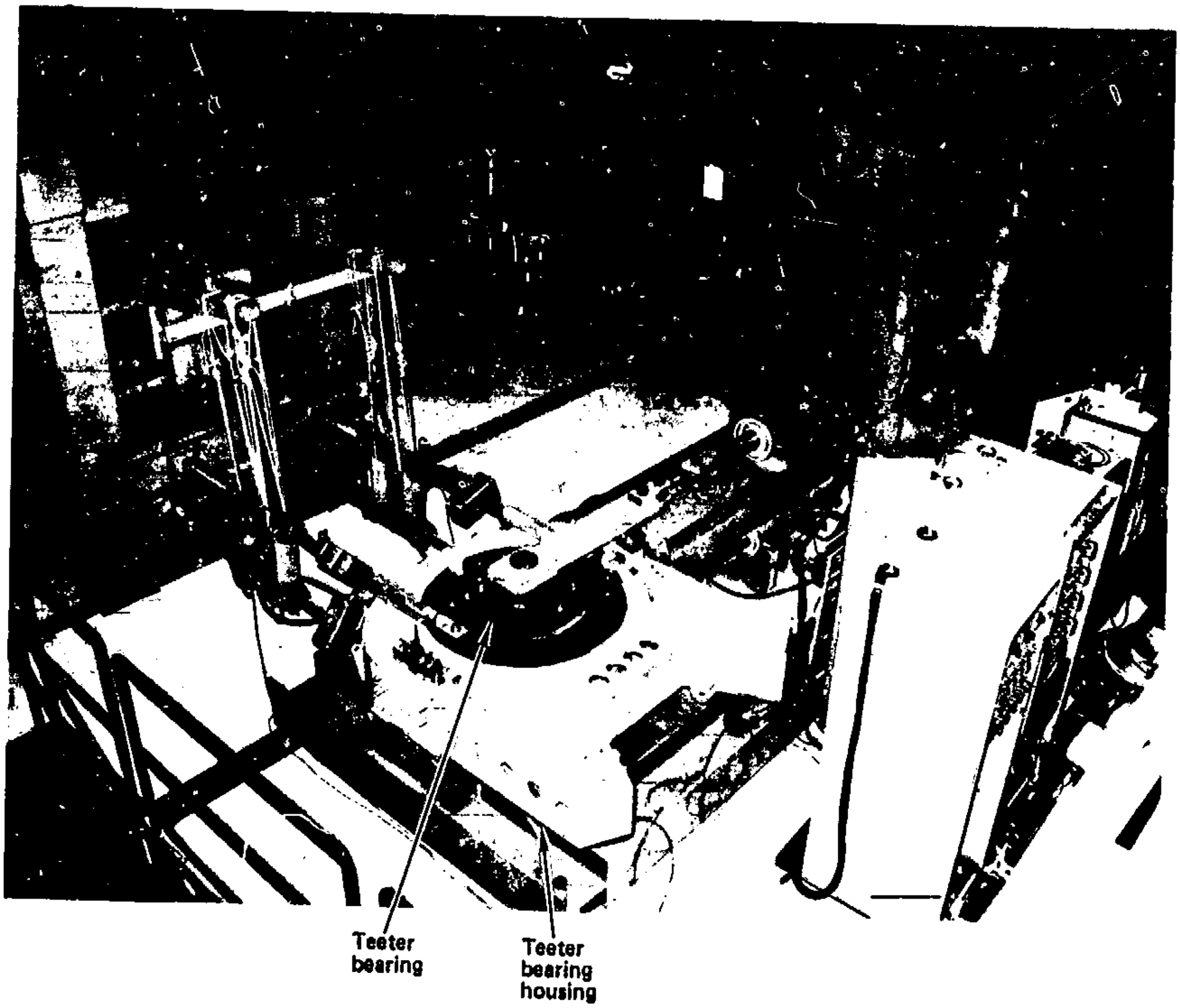

Figure 2-8. Teeter Bearing Life Test

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A major concern in the design of the welded steel rotor is the ability to assure safe operation for the structure's life in the cyclic load environment. The rotor is subjected to approximately 200,000,000 alternating stress cycles in its 30 year life. Fatigue cracks can develop due to internal material or weld flaws or from external damage. Therefore, a crack detection system was developed to provide for an automatic safe shutdown prior to the crack progressing to a critical failure size. Cracks detected can then be repaired and the system returned to operation. The rotor assembly is completely sealed except for a known orifice in each blade. Compressed air is then regulated through flow meters to maintain one psi in each blade. A schematic of the system is shown in Figure 2-9. An unbalance of flow between the two blades indicates a potential crack and initiates shutdown of the machine. Inspection and repair of most crack problems can be accomplished without removal of the rotor.

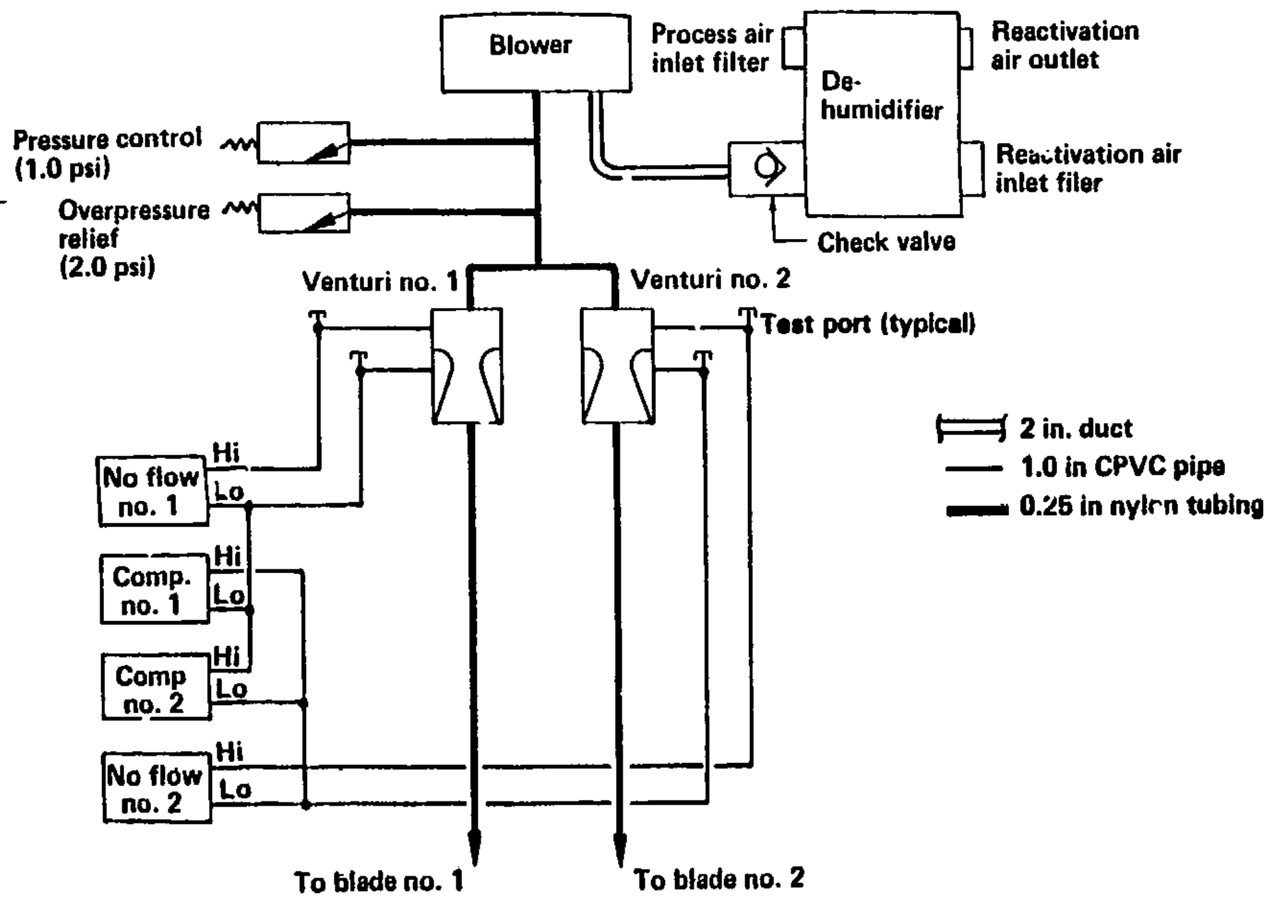

Figure 2-9. Blade Crack Detection System Block Diagram

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2.2.2 Drive Train

The drive train subassembly consists of a low speed shaft, quill shaft, gearbox, high speed shaft, couplings, rotor parking brake, and generator. These major components are shown in Figure 2-10.

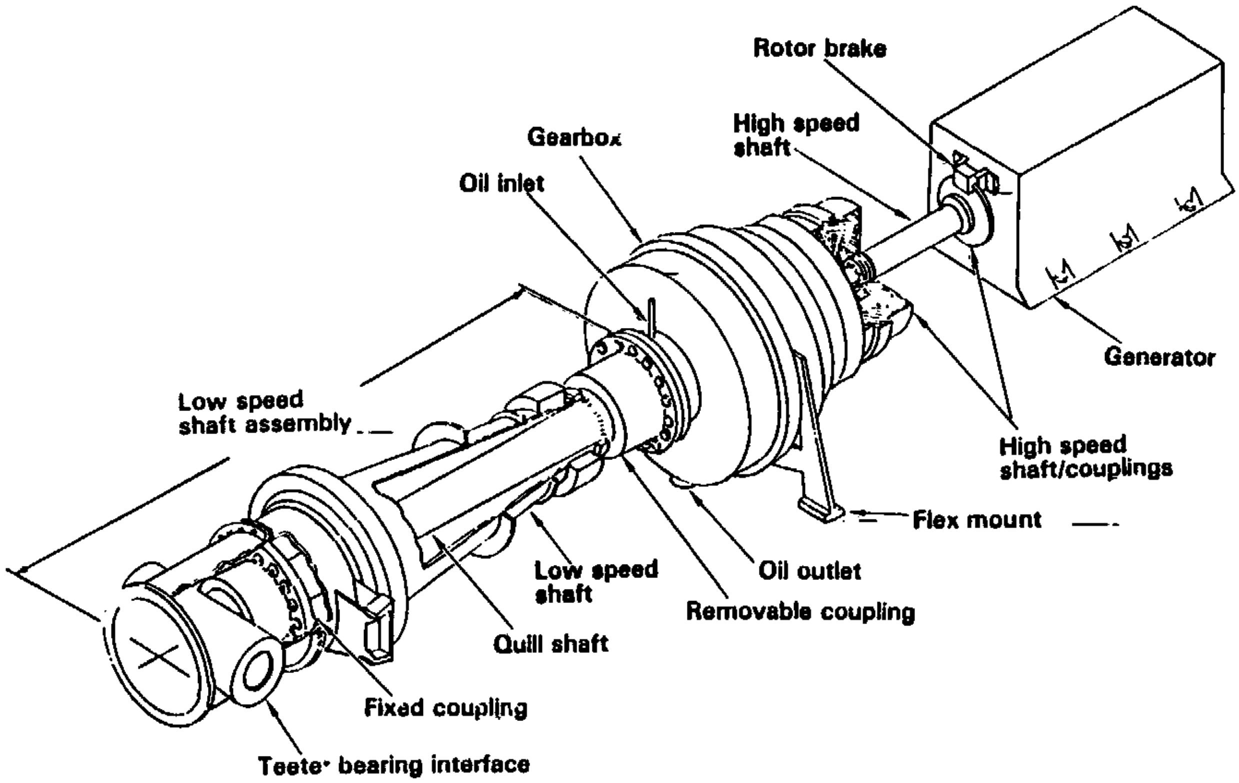

Figure 2-10. Drive Train

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The large diameter low speed shaft transfers the rotor forces into the nacelle structure through the two shaft support bearings. The forward bearing supports the radial load while the aft bearing transfers both thrust and radial loads to the nacelle. The rotor torque is transmitted to the gearbox through the "soft" quill shaft. The purpose of the softness is to reduce the two per revolution rotor torque fatigue effects at the gearbox and to improve the quality of the generator output. Figure 2-11 shows the shafting being installed in the nacelle. The quill shaft to gearbox coupling is produced by SKF of Sweden. This coupling is installed with a press fit and carries torque through friction. It is hydraulically actuated for ease of installation and disassembly.

Electrical power and control signals are transferred from the nacelle electrical power and control unit by brushes and a slip ring assembly on the quill shaft. The slip ring is split in two halves to allow removal and replacement without decoupling the drive train. This slip ring, as well as the yaw slip ring are produced by the Electro-Tec Corporation of Blacksburg, Virginia.

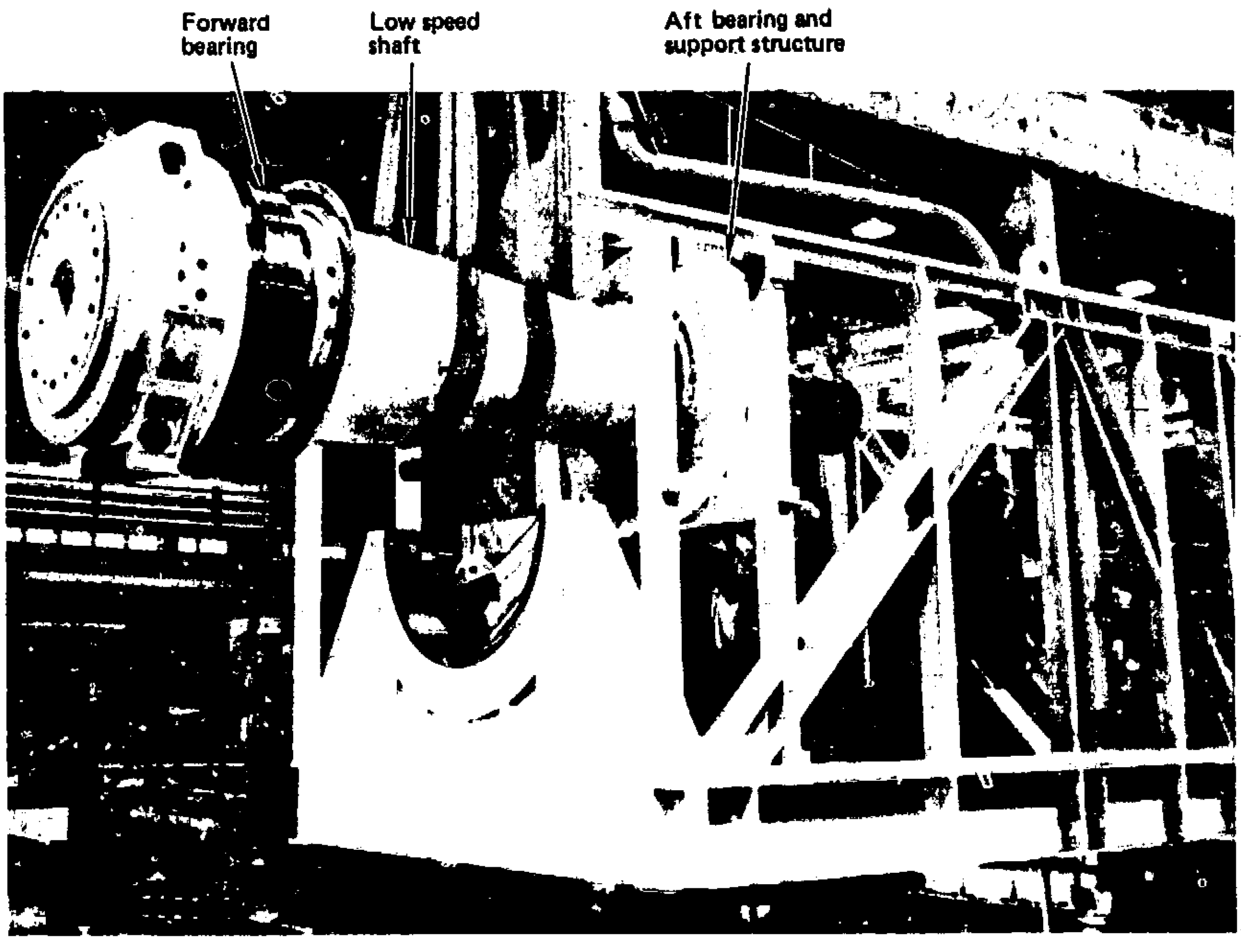

Figure 2-11. Low Speed Shaft Assembly Installation

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A 103:1 step-up of rpm from 17.5 to 1800 rpm is provided by a three stage epicyclic gearbox, which is smaller, lighter in weight, less expensive, more efficient and more tolerant to support deflections than a parallel shaft type gearbox with a similar rating. The low weight of the gearbox (39,000 lbs) simplifies the overall design of the supporting structure. It is flexibly mounted to the nacelle to reduce the effect of nacelle deflections on gear loads. Maintenance within the nacelle is enhanced by the small size of the gearbox. Figure 2-12 shows the gearbox being assembled at the Stal-Laval plant in Finspong, Sweden.

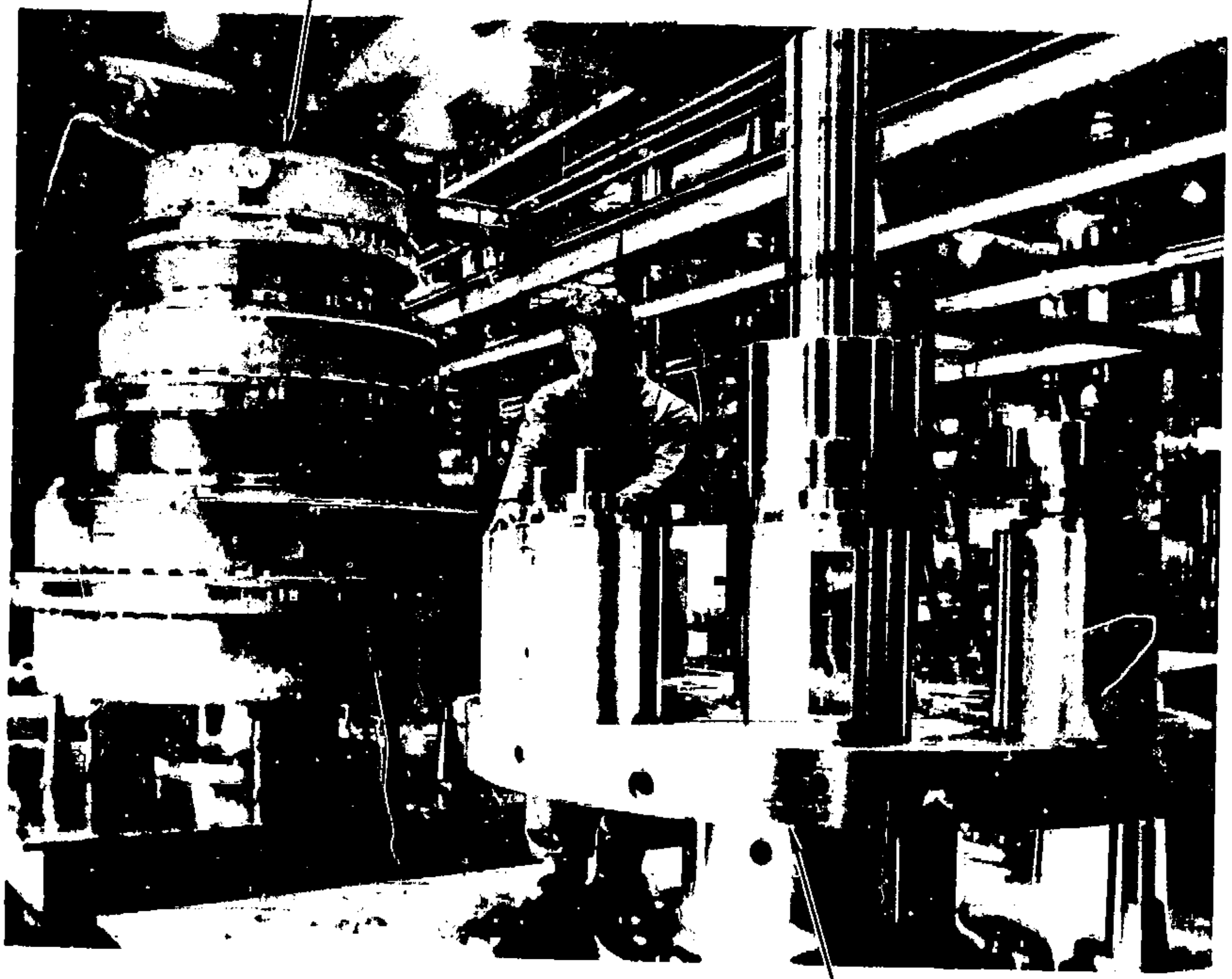

Figure 2-12. Gearbox Assembly

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The generator is a synchronous electrical generator, rated at 2500 kW. The unit is an open frame, drip proof, four salient pole brushless machine that operates at 1800 rpm and has a shaft mounted exciter. The generator utilizes journal type bearings lubricated by a forced oil system supplemented by a passive scoop lubrication system. Additional information on the generator bearing lubrication system is provided in Section 5.3.8. This generator (Figure 2-13) is provided by the Beloit Company of Beloit, Wisconsin.

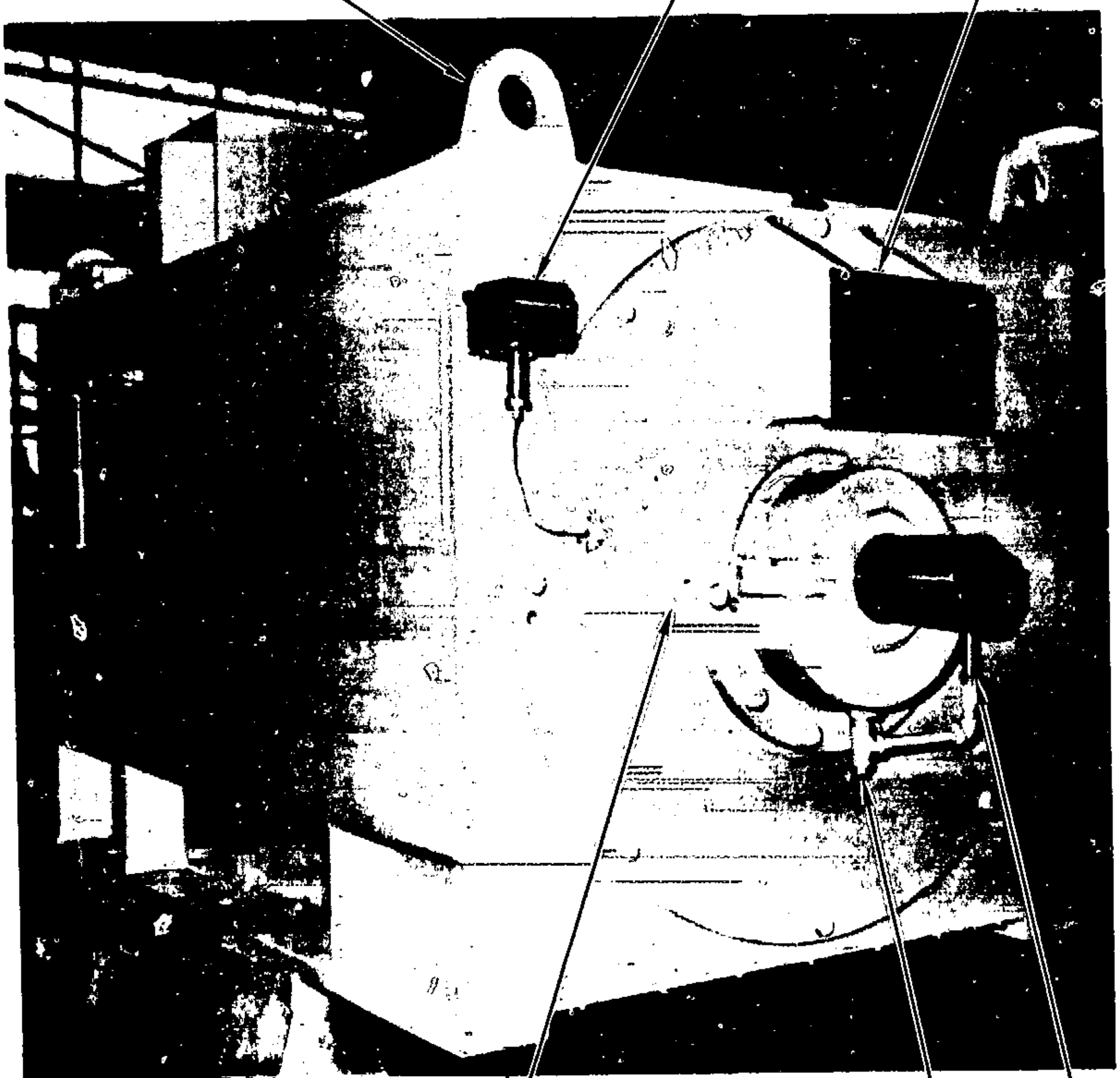

Figure 2-13. Generator

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The high speed shaft with disc-pac couplings is shown in Figure 2-14. It incorporates a chain drive sprocket and a parking brake disc. The chain sprocket is used in conjunction with an electric motor and gearbox to provide the ability to position the rotor for maintenance. The rotor parking brake minimizes rotor rotation when the WTS is not running. This prevents gearbox damage due to steady rotation without lubrication. The braking mechanism consists of a disc mounted on the high speed shaft and a spring actuated brake attached to the generator frame. The brake is disengaged by an electrically actuated hydraulic valve and engaged by spring force when the electrical circuit is open. The disc utilizes a replaceable element to minimize maintenance time in the event of brake disc wear.

As a result of the FMEA and maintainability studies, provisions for a positive mechanical lock mechanism are incorporated in the high speed shaft. This prevents rotation of the wind turbine during maintenance periods.

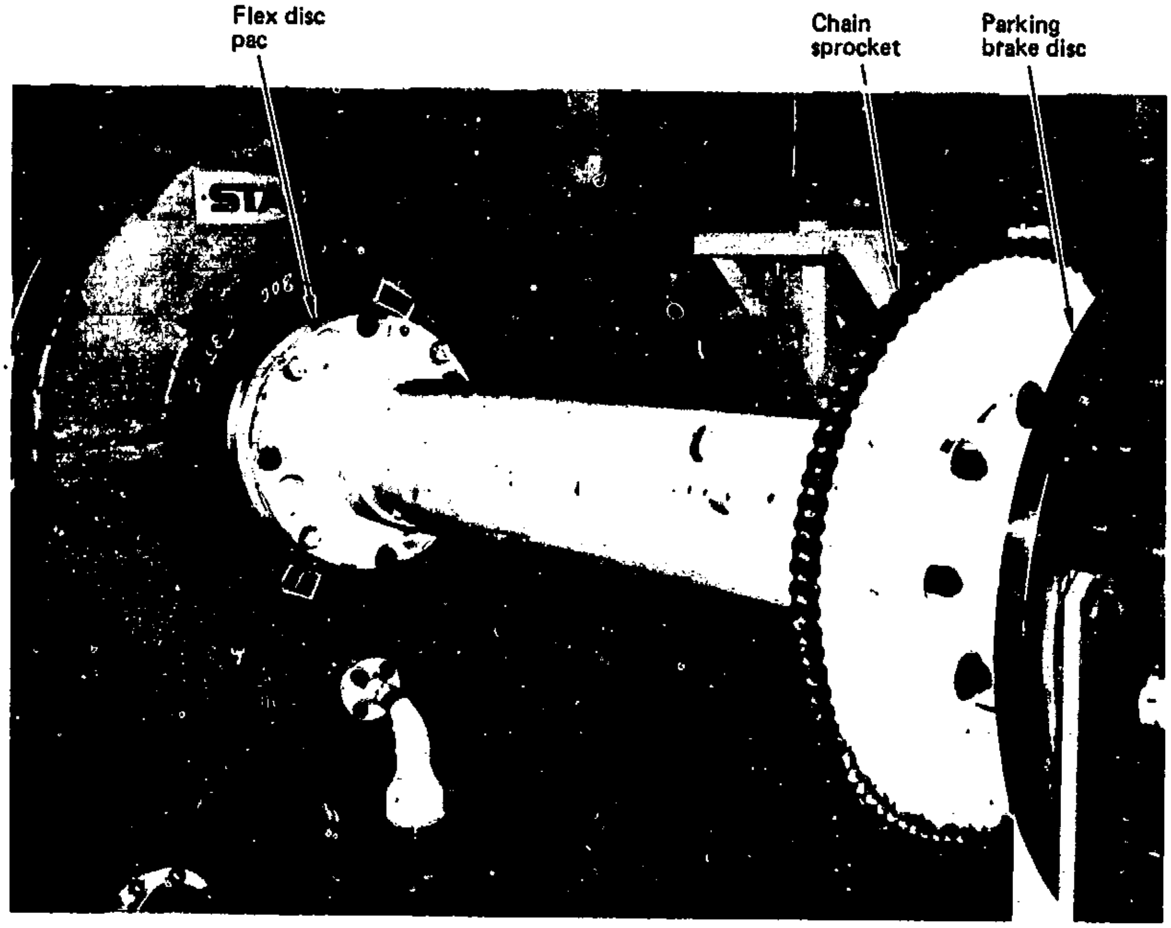

Figure 2-14. High Speed Shaft

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2.2.3 Nacelle

The nacelle houses the major subsystems of the MOD-2 WTS such as the drive train, generator with its accessories, yaw bearing and drive, and associated hydraulic systems for pitch and yaw control shown in Figure 2-15. Other equipment in the nacelle includes generator cooling air ducts, gearbox oil cooling radiators, maintenance lighting fixtures and wall plugs, electronics cooling and heating system, general nacelle air circulating system, fire protection equipment, and maintenance provisions equipment.

Its primary functions are to provide a rigid mounting platform for the system components, react to rotor loads and provide environmental protection for the components.

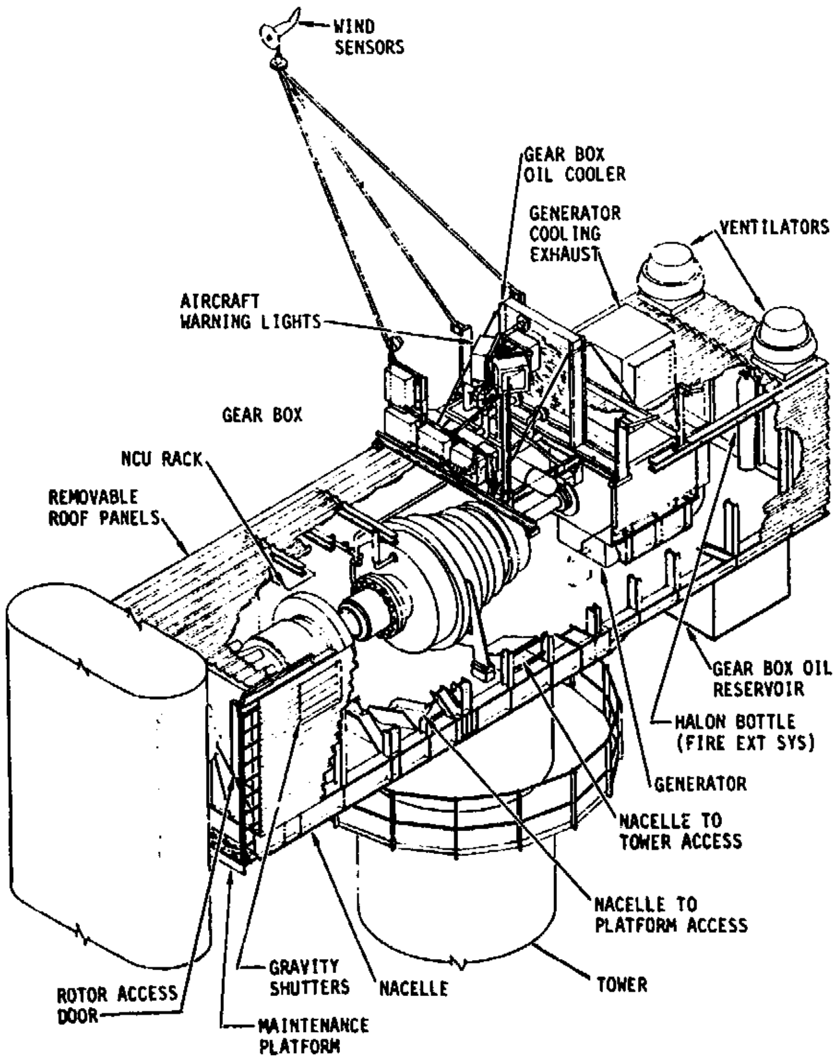

Figure 2-15. Nacelle Equipment Installation

The nacelle structure is of welded ASTM A36 and A633 steel truss construction and manufactured by Bucyrus-Erie Inc., in Pocatello, Idaho. Its primary dimensions are: 36.8 feet long, 9.3 feet high, and 11.3 feet wide. The top and sides are sheathed with corrugated steel sheets, and the floor is steel safety plate. A central floor hatch provides normal access from the tower, and a second hatch provides access to the tower platform.

Primary considerations in the design of the nacelle were maintainability and safety. The MOD-2 design utilizes two overhead monorails for equipment handling. One of these extends through a large door in the downwind end of the nacelle. It can be used in conjunction with a portable hoist to raise equipment from the ground. There are also large overhead hatches for the installation or removal of large pieces of equipment. Care has been taken to allow sufficient room for maintenance procedures to occur within the nacelle.

Safety features of the nacelle include an integral fire extinguisher system, non-powered emergency manlowering devices for emergency egress, the ability to remove an injured person on a stretcher, and the positive mechanical shaft locking device.

The nacelle also houses the yaw drive system. The yaw system connects the nacelle to the tower as shown in Figure 2-16. It rotates the rotor and nacelle into the wind at a rate of 1/4 degree per second, and holds them in position as commanded by the yaw control system. All rotor and nacelle loads are transferred to the tower through the yaw bearing which is of a three row roller configuration with an internal ring gear. The raceway diameter is approximately 120 inches in order to handle the large overturning moments and to react to the rotor torque.

Figure 2-17 shows the yaw bearing produced by ROTEC, Inc., of Aurora, Ohio.

Proper nacelle orientation to the wind is maintained by the yaw control system. The control system utilizes a wind sensor to determine wind direction. To allow for the short period, wide directional variations common at low wind speeds, the yaw control system uses averages to determine wind direction. The control system then provides commands to the yaw drive system with the goal of maintaining orientation within ±7 degrees of the wind direction to minimize energy losses. If the average deviation over an approximate 6 minute period exceeds ±7 degrees, the control system will initiate yaw drive to align the nacelle with the wind vector. If the yaw error, averaged over a 25.6 second period, exceeds 20 degrees, a similar yaw correction is made and if the yaw error averaged over 2 minutes exceeds 20 degrees the machine automatically shuts down.

The yaw drive system operates at 2,000 psi and consists of an electric motor, hydraulic pump, heat exchanger, reservoir, filters, and the necessary valves and tubing. These drive a hydraulic motor which runs a pinion meshing with the gear on the inner face of the yaw bearing. The drive pinion and shaft are protected from overload and subsequent mechanical damage by limiting the capacity of the yaw drive hydraulic motor.

Six brakes hold the nacelle from inadvertent yawing due to wind loads during "no yaw" operation. The yaw brake calipers are spring actuated and hydraulically released through the yaw drive hydraulic system. This is a failsafe feature assuring that the brakes are applied if there is a hydraulic failure.

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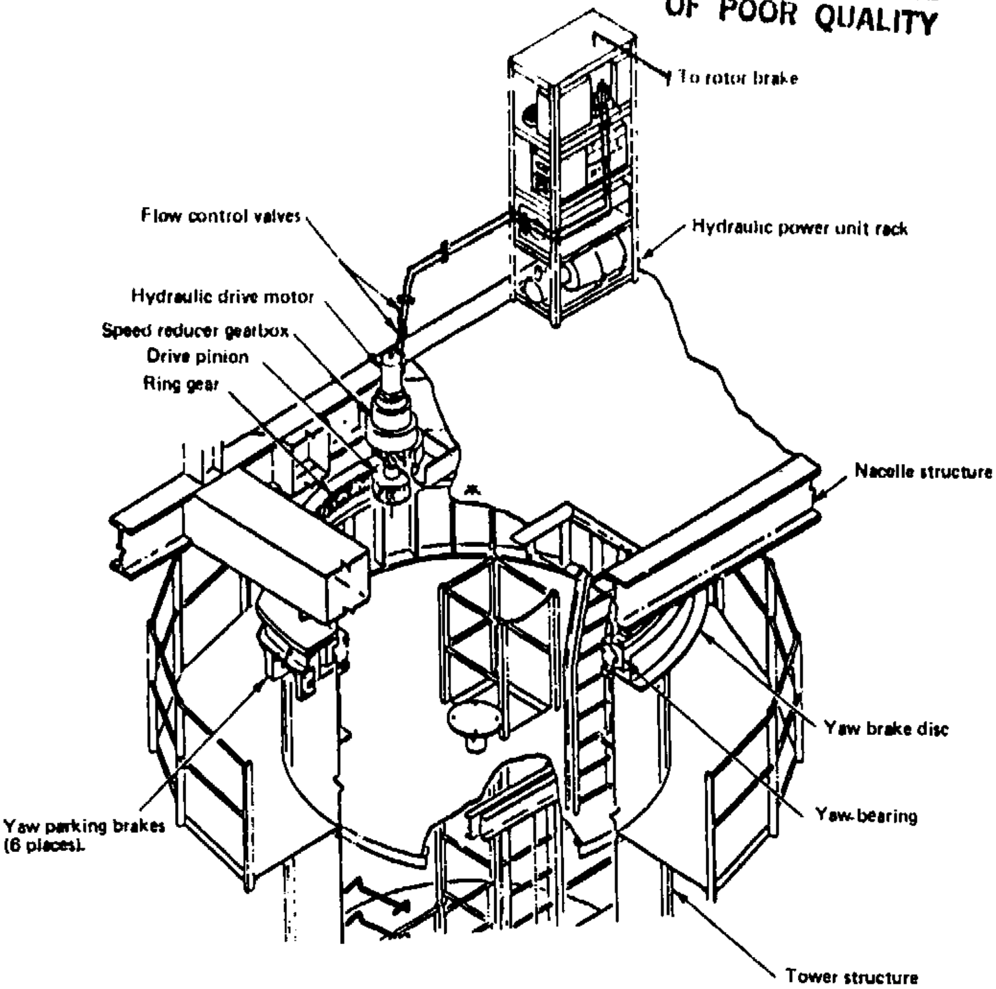

Figure 2-16. Yaw Drive Installation

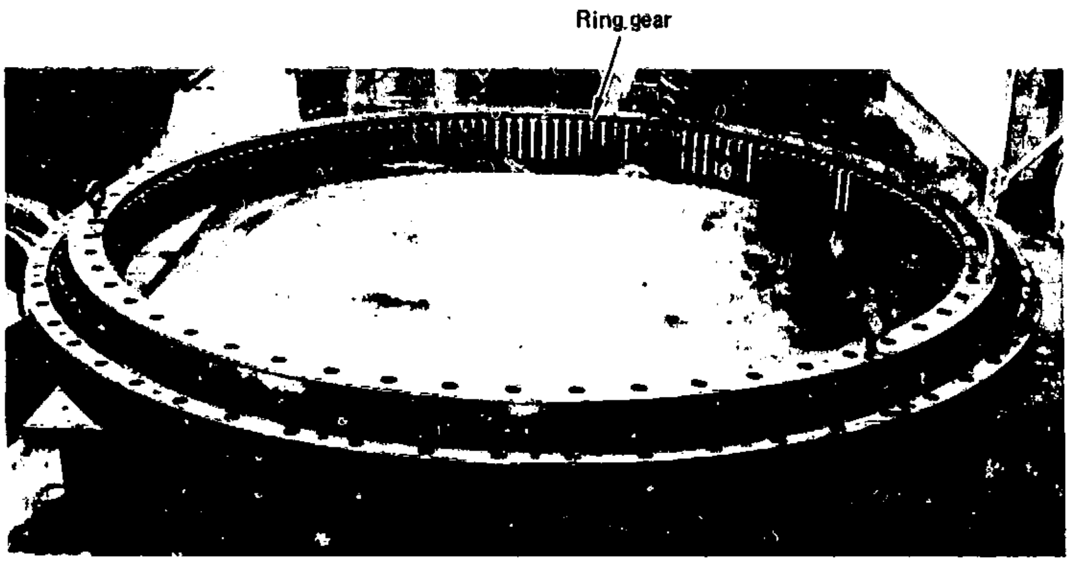

Figure 2-17. Yaw Bearing

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2.2.4 Tower/Foundation and Facility Layout

The nacelle assembly is supported by a 193 foot tall cylindrical welded ASTM A572 steel tower. The tower is 10 feet in diameter with a base section flaring to 21 feet in diameter at the ground. It is bolted to a foundation of reinforced concrete as shown in Figure 2-18. At Goldendale, 72 rock anchors 28 feet long attach the foundation to bedrock. The tower is manufactured and erected by Chicago Bridge and Iron Company.

The tower is designed to have a low natural bending frequency (approximately 1.3 per rotor revolution) to reduce the alternating rotor loads transmitted to the tower.

An external platform near the top of the tower provides access to service the yaw brakes and wind sensors.

The tower contains an internal cable/drum type lift to provide transportation from the ground to nacelle. The lift ends at a platform near the top of the tower, with final nacelle access by a ladder as shown in Figure 2-16. A ladder with safety cable runs the entire height of the tower to allow access/egress in the event of a lift failure. The power and control cables run from the electrical slip rings at the top of the tower, down the tower side to the bus tie contactor unit located on a separate concrete pad external to the tower. A step-up transformer is also located on this pad. Additional electrical and control equipment is located in the tower base. The power cable lines are buried from the tower to the utility connection at the transformer pad.

A typical facility layout is shown in Figure 2-19 and an aerial view of the 3 unit facility layout is shown in Figure 2-20.

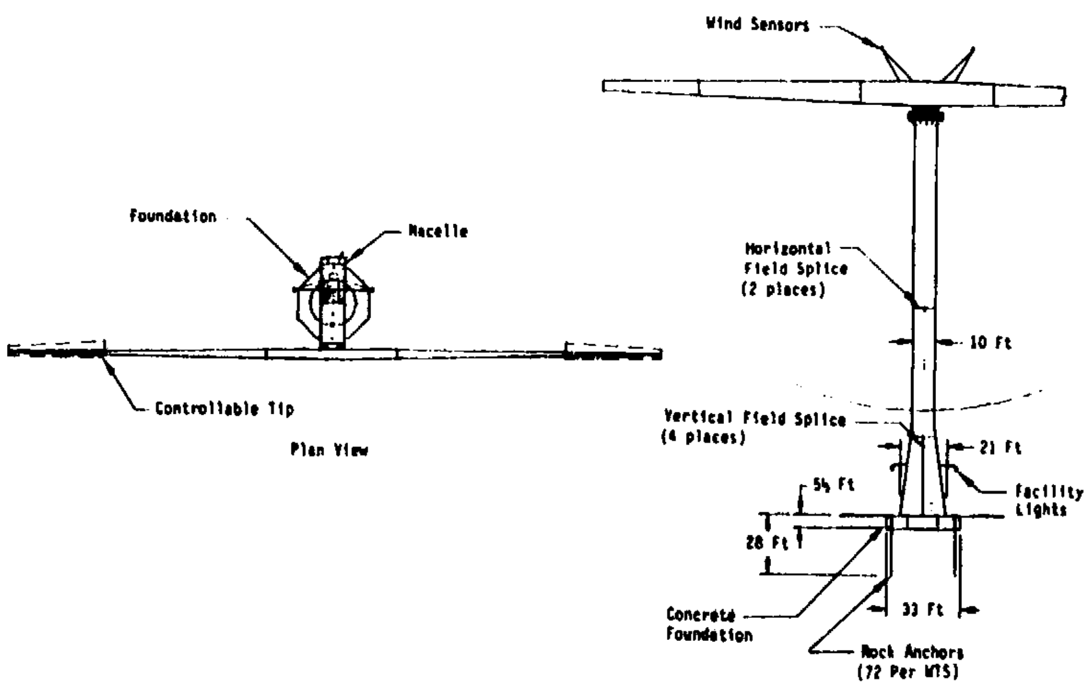

Figure 2-18. Tower Foundation

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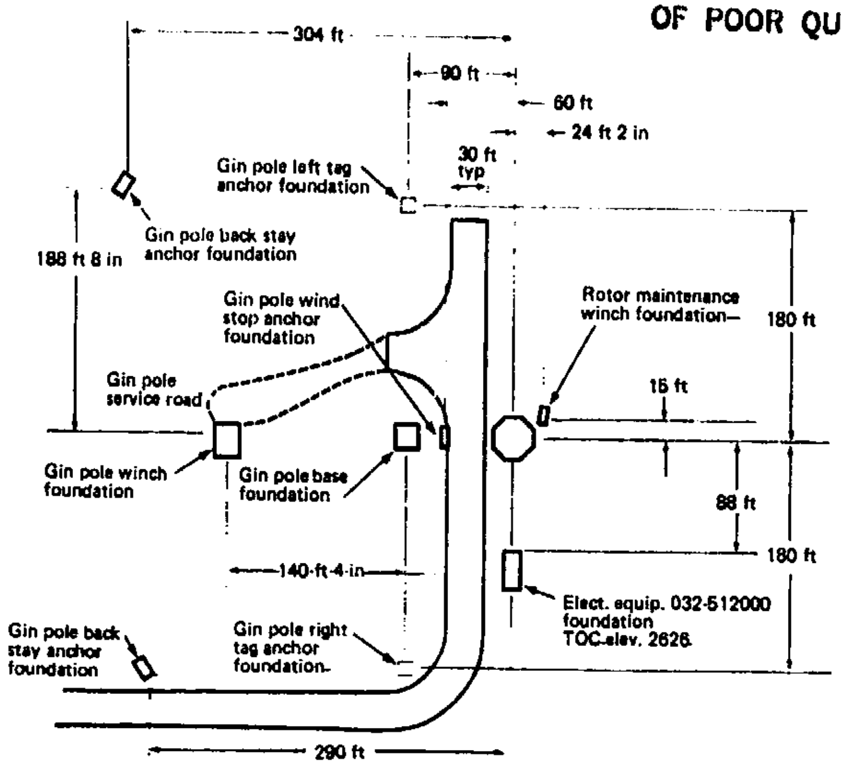

Figure 2-19. Facility Layout

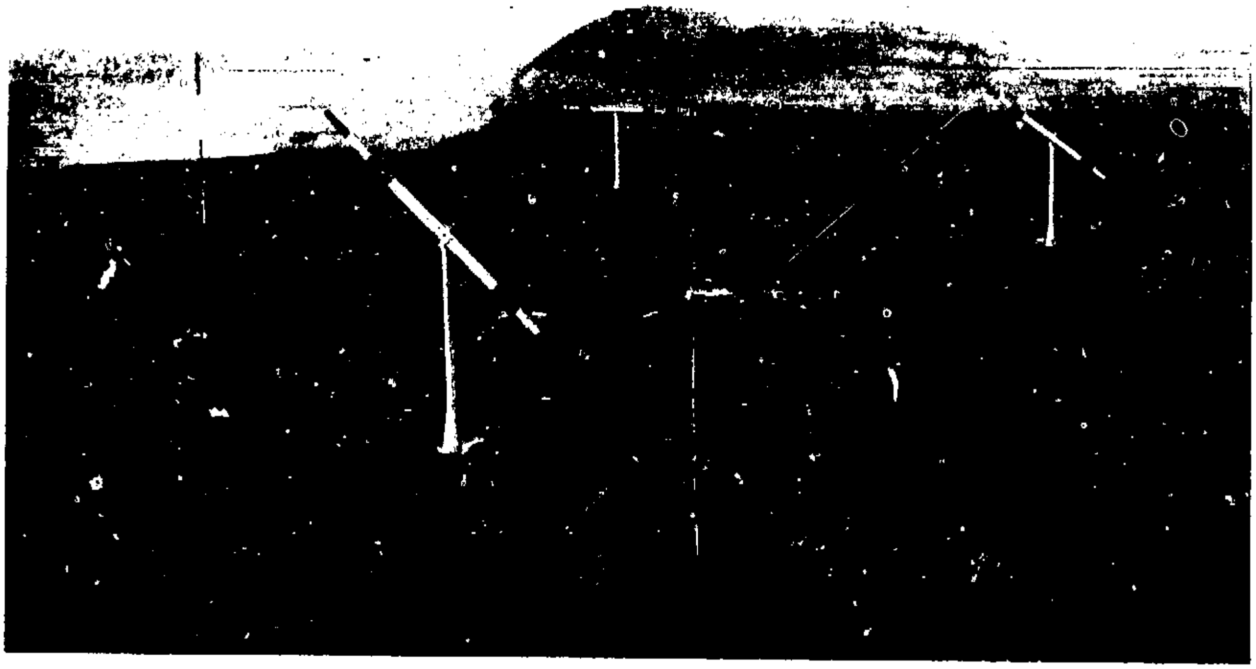

Figure 2-20. Goldendale Site

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2.2.5 Electronic Control System

The control system provides the sensing, computation, and commands necessary for unattended operation of the WTS as shown in Figure 2-21.

The controller is a microprocessor which is located in the nacelle control unit and initiates startup of the WTS when the wind speed is within prescribed limits. After startup, it computes blade pitch and nacelle yaw commands to maximize the power output for varying wind conditions. Continuous monitoring of wind conditions, rotor speed power and equipment status is also provided by the microprocessor which will shut down the WTS for out-of-tolerance conditions.

A control panel and Cathode Ray Tube (CRT) terminal are located in the tower base to provide operating and fault data displays and manual control for maintenance. A remote CRT at the utility substation will provide display and limited WTS control. Fault code history display is provided at the remote CRT to identify maintenance requirements prior to dispatch of the maintenance crew.

The WTS is protected from computer system failure by an independent failsafe shutdown system. The failsafe system also provides sensor redundancy on critical components, and initiates shutdown independent of the primary control system when necessary. The design of the failsafe system was governed by the results of the FMEA (Reference 2). As a result of the failure incident resulting in overspeed on Unit #1, a third independent set of valves provides shutdown for an overspeed condition. Figure 2-22 shows the automatic shutdown system employed to assure failsafe operation.

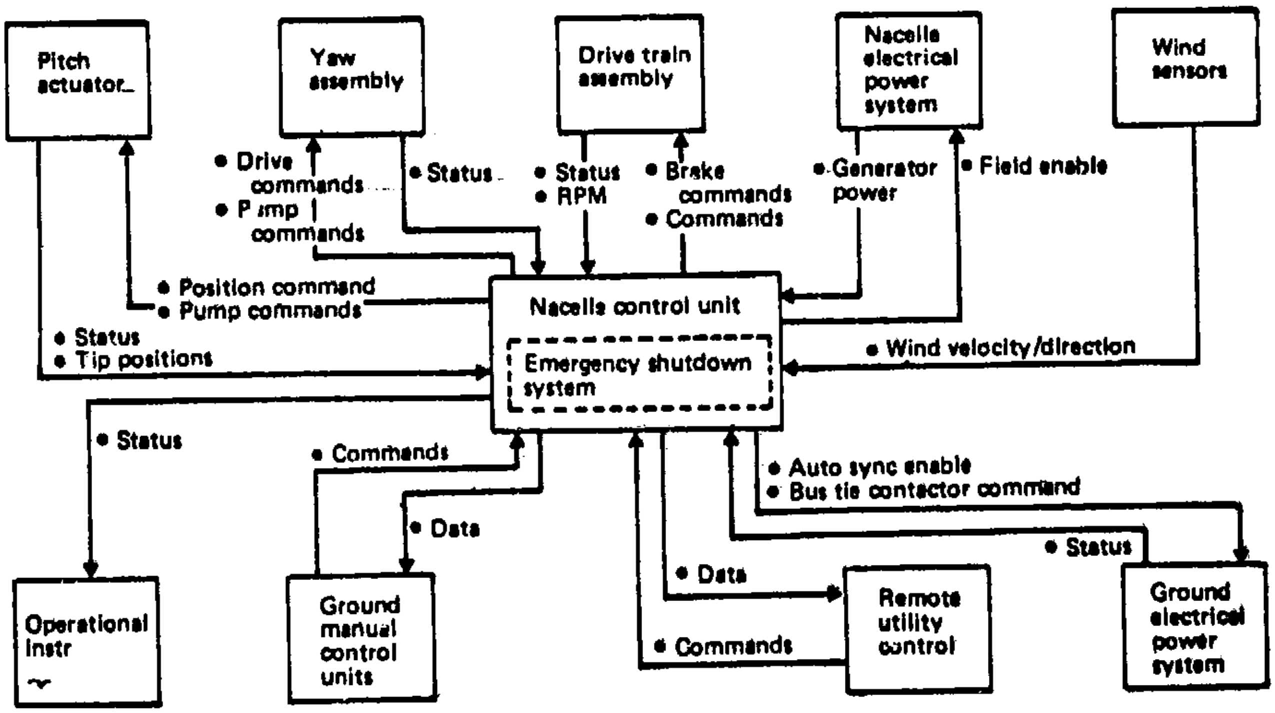

Figure 2-21. Control System Block Diagram

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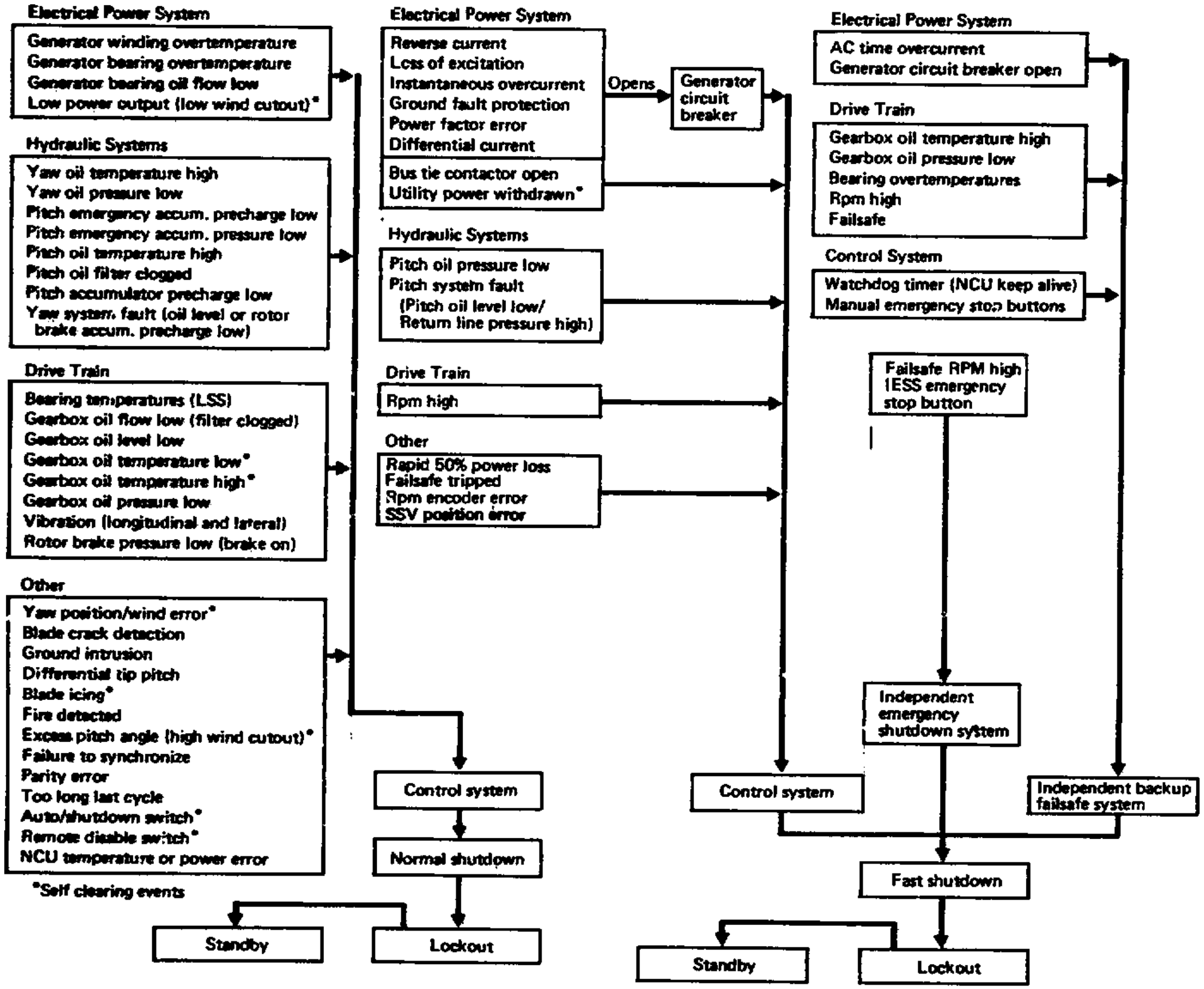

Figure 2-22. Safety/Shutdown System

The control software for the microprocessor occupies approximately 12,000 bytes of programmable read-only memory with an additional 4,000 bytes of random access memory for operating and history data storage. The software control cycle is accomplished at a rate of 10 Hertz to provide a one Hertz response digital feedback control to the blade pitch system. In addition, each program cycle also samples all sensors, schedules the proper operating mode, and generates commands as required to control nacelle position with respect to the wind.

2.2.6 Electrical Power System

The WTS electrical power system is designed to deliver power to a utility transmission network. The system consists of the electrical equipment required for the generation, conditioning and distribution of electrical power to the utility and within the WTS as shown in Figure 2-23. In normal operation, the generator receives its power in the form of torque at synchronous speed from the gearbox. Electrical power at appropriate voltage is delivered at a utility interface point which is the output side of a fused manual disconnect switch located at the foot of the tower. Once the WTS and the utility are electrically connected, the existence of the tie will automatically result in generator voltage and frequency control since the utility power grid is effectively an infinite bus to the WTS. Thus constant generator and rotor rpm will be maintained.

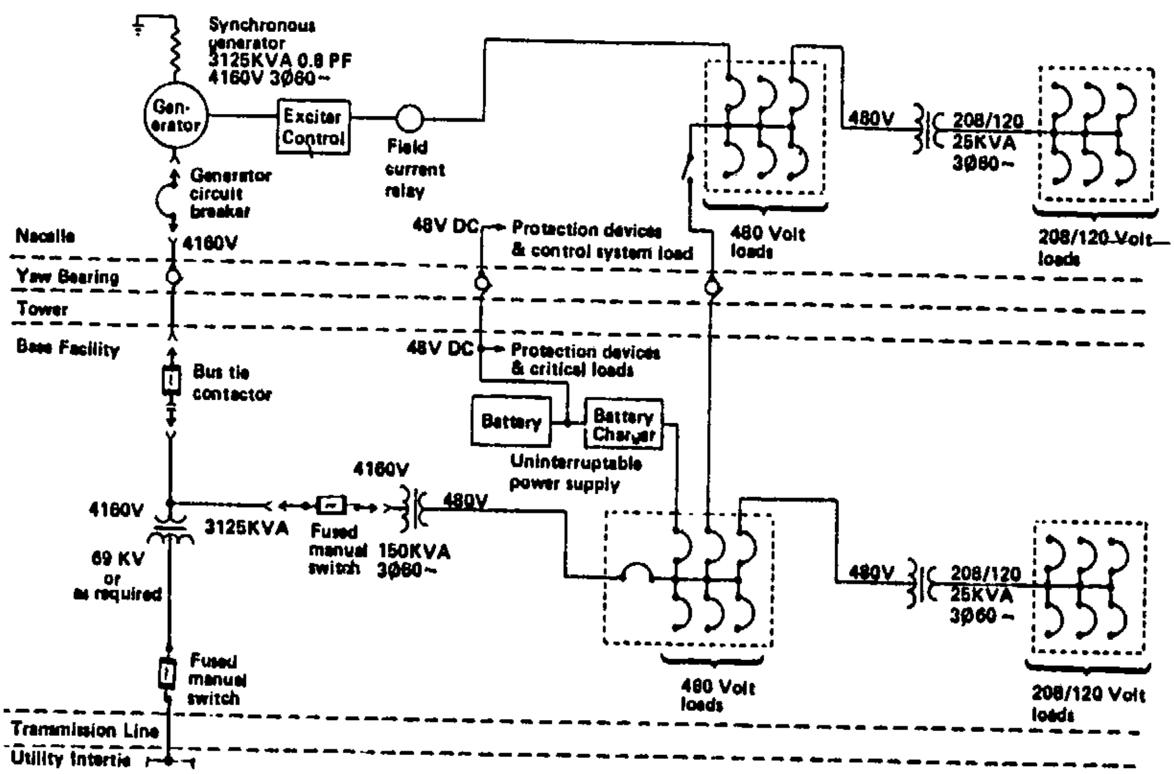

Figure 2-23. Electrical Power System Block Diagram

The MOD-2 electrical power system employs a four-pole synchronous generator containing an integral brushless exciter. It is a 3 phase, 60 Hertz, 4160 volt generator rated to provide 3125 KVA at 0.8 power factor, i.e., 2500 kW, at altitudes to 7,000 feet, or temperatures to 50 degrees C. Excitation control is provided to maintain proper voltage prior to synchronization with the utility and to provide a constant power factor output afterwards. Protective relays are provided to guard against potential electrical faults, out-of-tolerance performance or equipment failures. These relays will detect overvoltage, loss of excitation underfrequency, overcurrent, reverse phase sequence, reverse power and differential current, and will protect the system by inhibiting synchronization, directing the control system to shut down or, if required, trip the generator circuit breaker. The operation of these protective relays was governed in part by the results of the FMEA and standard utility practice.

Power is delivered to the utility transmission line through a bus tie contactor. Its operation is controlled by automatic synchronization equipment, located at the tower base. Accessory power for operation, control and maintenance is obtained from the utility or generator output depending on the operating mode, and is internally conditioned to appropriate voltage levels. Eight six volt batteries in series floating across a charger, provides an uninterruptable power supply for operation of protective devices and critical loads.

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2.3 SYSTEM PERFORMANCE

The performance of the MOD-2 WTS is specified by its system efficiency curve, its power and energy output distributions, and its annual energy output.

The efficiency of the MOD-2 WTS is described by a non-dimensional number known as the power coefficient. Physically, the power coefficient is that fraction of the wind's kinetic energy passing through the rotor disc which is converted into mechanical or electrical energy.

The system power coefficient for the MOD-2 WTS is shown in Figure 2-24. As indicated on the figure, the system power coefficient is derived from the rotor power coefficient and the efficiencies of the drive train and electrical subsystems. Also indicated on Figure 2-24 is a rated power line for 2500 kW at sea level standard conditions.

The system efficiency curve can be translated into a power distribution curve when the atmospheric density is given.

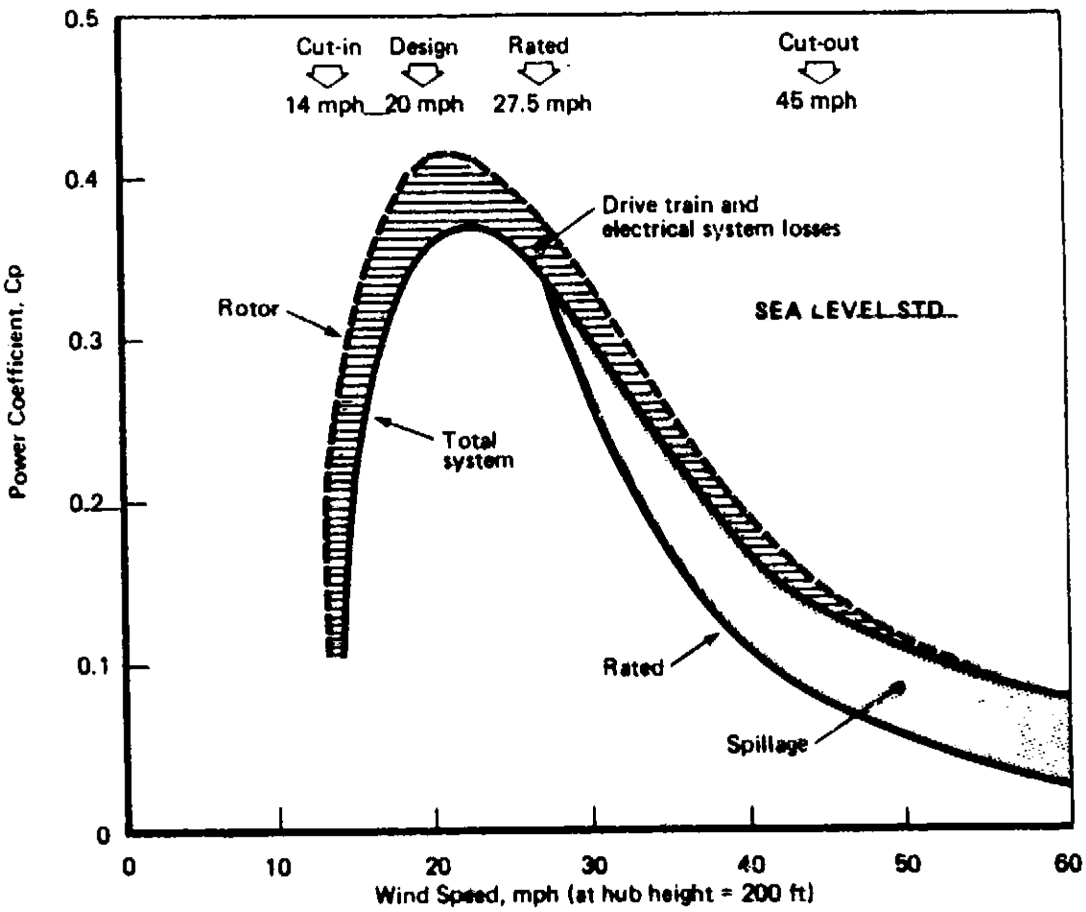

Figure 2-24. Cp Versus Wind Speed - Sea Level Std.

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The MOD-2 system design-power output distribution is shown in Figure 2-25 for standard temperature at sea level and 7,000 foot altitude. The cut-in, rated and cut-out wind speeds are also indicated on this figure. Actual operational performance currently experienced during the checkout and acceptance test phase is discussed in Section 5.0.

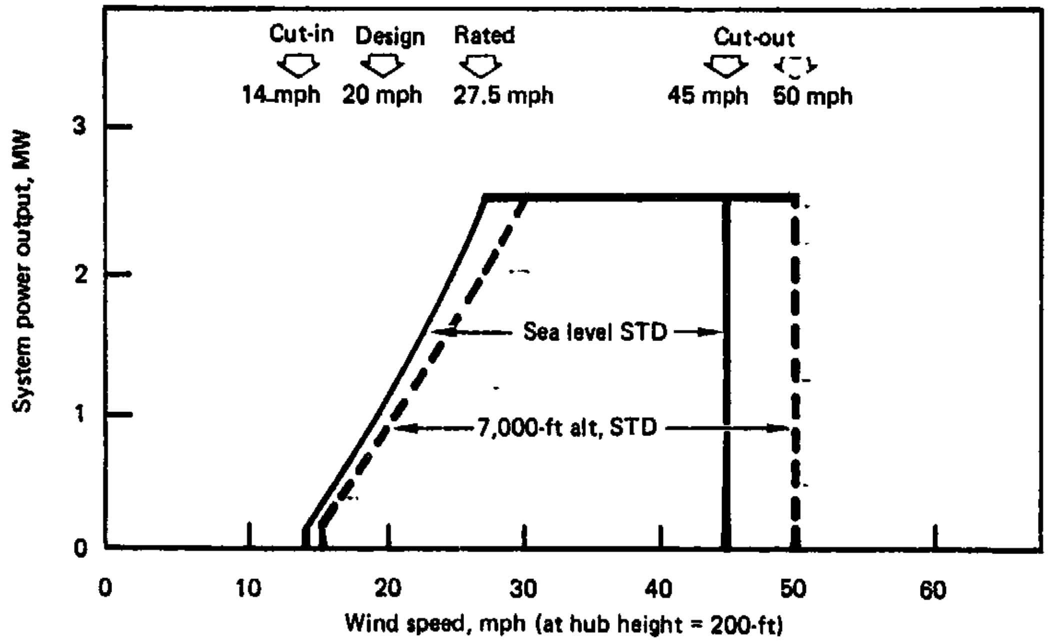

Figure 2-25. System Power Output Versus Wind Speed

The energy output frequency distribution for the MOD-2 WTS is derived by combining the output power distribution curve with the wind frequency distribution for a given site. The design energy output frequency distribution for the MOD-2 WTS is shown in Figure 2-26 for sea level standard conditions. The associated design wind frequency distribution is presented in Figure 2-27. This design wind frequency distribution was specified by the NASA for MOD-2 design. It represents a typical wind environment for potential wind turbine sites. The frequency distribution is typical of a site with a mean wind speed of 14 mph at an elevation of 30 feet and was used for optimization of the WTS characteristics.

The area under the curve is indicative of the time the WTS spends in different operation regimes. Approximately 59% of the time the WTS experiences winds between cut-in (14 mph) and rated (27.5 mph), while 18% of the time the wind speed is between rated and cut-out (45 mph). The remaining time (23%) the wind turbine experiences either winds too light or too strong for operation. Of this idle time, most occur due to low wind speeds.

The annual energy output of the MOD-2 WTS (based on the design wind frequency distribution) is obtained by integrating the energy frequency distribution between the cut-in and cut-out wind speeds. For the MOD-2 WTS, the total annual energy is 9,753,000 kWh, including the 0.967 calculated system availability. The MOD-2 WTS derives 61% of its energy when operating between the cut-in and rated wind speeds, while 39% of the annual energy is derived when operating above rated wind speed.

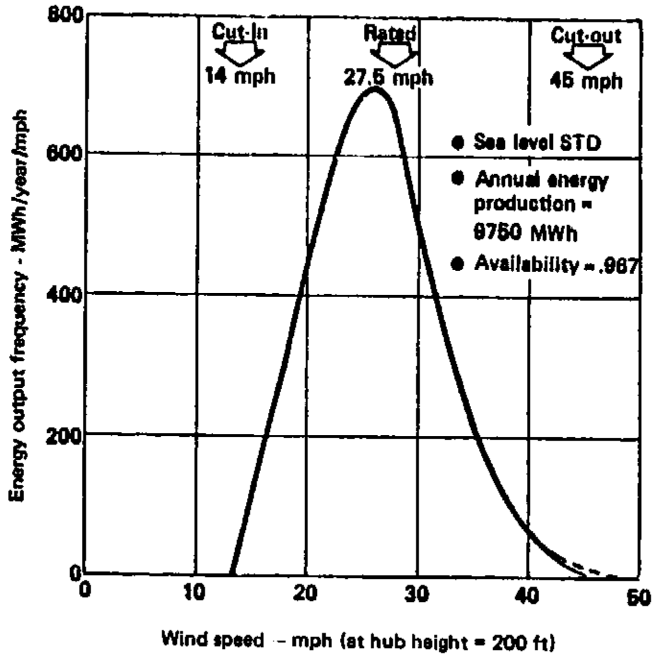

Figure 2-26. Energy Output Frequency Distribution

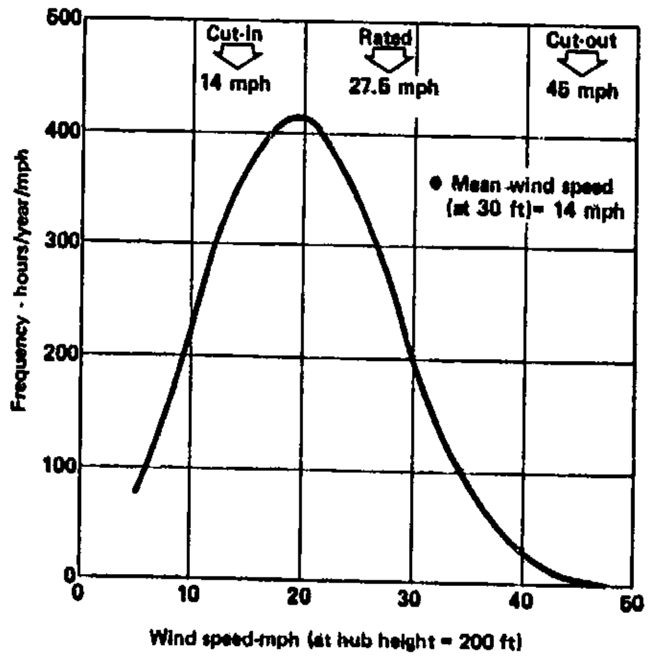

Figure 2-27. Design Wind Speed Frequency Distribution.

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2.4 WEIGHT

Table 2-1 presents a summary weight breakdown. The rotor weight includes the teeter bearing and rotor cap structure to the drive train interface (lift weight at installation). The combination of drive train and nacelle represents the lift weight at installation onto the tower.

Table 2-1. Weight Summary

ELEMENT	WEIGHT (LB)
Rotor	198,000
Drive Train	93,000
Nacelle	82,000
Tower	255,000
Total Above Foundation	628,000

2.5 COST

2.5.1 100TH Unit Production and Maintenance Costs

Estimated 100th production unit costs for the MOD-2 WTS are summarized in Table 2.2. The turnkey estimates include all costs associated with the manufacture, assembly and installation of the WTS. The manufacturing costs are based upon a dedicated high rate production facility producing 20 units per month with installation in farm sizes of 25 units.

Table 2-2. 100th Production Unit Costs ($1980)

TURNKEY ACCOUNT	COST ($1,000)
Site Preparation	201
Transportation	37
Erection	163
Rotor	370
Drive Train	477
Nacelle	262
Tower	344
Initial Spares & Maint. Equip.	19
Non-recurring	44
Total Initial Cost	1,917
Fee 10%	192
Total Turnkey C	2,109
Annual Operations and Maintenance	19

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The estimated costs of operations and maintenance (O&M) for the mature production units in a 25 unit farm are based on the reliability analysis of Mean Time Between Failure (MTBF) and the Mean Time To Repair (MTTR) calculations. These data, as provided in Section 2.6, define the maintenance manloading requirements and the spares and equipment requirements for annual O&M costs.

The data in Section 2.6 substantiate the turnkey account of spares and maintenance equipment and the annual O&M costs as tabulated below:

Unscheduled Maintenance	6,900 mhrs/year
Scheduled Maintenance	1,825 mhrs/year
Administrative Tasks	925 hrs/year
Total	9,650 mhrs/year

9,650 - 25 WTS x $25/hr. = $9,650/Yr./WTS

OR

2-2 person shift/day, 6 days per week = $10,000/Yr./WTS
plus contingencies

Parts and outside services = $8,750/Yr./WTS

Total Annaul O&M = $18,750/Yr./WTS

The Cost of Energy (COE) is then based on the contract defined formulation:

$$COE = \frac{I.C. \times FCR + AOM}{AEP}$$

where I.C. = Total WTS Cost = $2,109,000
FCR = Fixed Charge Rate = 18% per year
AOM = Annual Operations and Maintenance Cost = $19,000
AEP = Annual Energy Production = 9,753,000 kWh
COE = 4.09 ¢/kWh (1980$)

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2.5.2 Initial Production Costs

Estimated initial recurring production costs for the first three MOD-2 units are shown in Table 2-2A.

Table 2-2A. MOD-2 Estimated Unit Cost Breakdown

DOLLARS IN THOUSANDS

		UNIT 1	UNIT 2	UNIT 3
HOURS		61,709	55,540	52,218
DOLLARS -	DIRECT LABOR	$ 843	$ 758	$ 712
	FRINGE BENEFITS	330	297	279
	OVERHEAD	442	399	375
	TRAVEL	203	183	173
	ADMINISTRATIVE	545	491	462
	DELIVERABLE MATERIAL	2,143	2,078	2,052
	M&E INSTALL	375	338	316
	SITE PREPARATION	332	298	281
	TOWER ERECTION	87	78	73
	SITE I & CO	581	523	491
	ASSEMBLY & TEST SPARES	77		
	OTHER	135		
COST TOTAL		$ 6,093	$ 5,443	$ 5,214

2.6 SAFETY, RELIABILITY, AND MAINTAINABILITY

Recognizing the importance of developing a safe and reliable system, considerable effort was expended to ensure that the MOD-2 design was inherently reliable and free of safety hazards to the public and maintenance personnel. Early in the preliminary design phase, a thorough Failure Mode and Effect Analysis (FMEA) covering more than 750 potential failure modes was initiated, resulting in numerous design changes to eliminate or reduce the consequences of hardware failures (see Section 2.7). Detailed reliability failure rate estimates were prepared down to the component level. Each component was assigned a failure rate based on past experience with similar components in the electrical utility and commercial aircraft industries. Trade studies were conducted on individual major components to arrive at a balance between reliability and cost with the objective of achieving the lowest cost of electricity. Selective redundancy was applied where the need was indicated by the FMEA or initial reliability estimates.

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In order to achieve a high in-commission rate (availability), it was also necessary to ensure that equipment failures were easily repaired and the system restored to operational status. Each component was examined from the standpoint of accessibility, the need for preventative maintenance, spares support and materials handling. Detailed estimates of repair times and maintenance manhour requirements were prepared and a maintenance concept developed.

Along with the FMEA, a safety gross hazards analysis was performed to ensure that applicable OSHA requirements were met or exceeded and to incorporate safeguards to the public such as aircraft warning lights, an ice detection system and a rotor crack detection system.

The results of these analyses are presented below; and the experience to date on the operational MOD-2 units is presented in Section 5.5.

2.6.1 Safety

A MOD-2 safety analysis was conducted to identify personnel hazards associated with the operations and maintenance of the MOD-2 WTS and to ensure that such hazards were eliminated or reduced to an acceptable level. Potential safety problems were identified by reviewing the MOD-2 drawings and specifications, failure mode and effects analysis, and preliminary maintenance scenarios. All potential hazards were noted and corrective action implemented where necessary. Since the MOD-2 is an unmanned system, hazards can only occur: (1) from aircraft impacting the tower, nacelle, or rotor, (2) to the public as a result of rotor structural failures, ice being thrown off the rotor, unauthorized entry into an operating system, or (3) during maintenance.

Table 2-3 contains a summary of the potential safety hazards and the applicable corrective actions.

2.6.2 Reliability

The MOD-2 WTS availability goal is .96 with a minimum requirement of .90 for mature production units. Achievement of a .96 availability is realistic when compared to conventional power plants. The primary cause of low availabilities of conventional power plants are the outages due to the fuel fired steam generator which does not have a counterpart on WTS.

Cost vs. availability/reliability trade studies were conducted to arrive at design solutions that yielded the lowest cost of electricity. These analyses show that the .96 availability is a cost effective goal. Availability estimates were compiled for all major MOD-2 WTS components down to the piece part level using failure rates and repair times being experienced on similar components in commercial applications. Table 2-4 summarizes the availability analysis.

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Table 2-3. Safety Precautions

ITEM	CORRECTIVE ACTION
Obstruction to Aircraft	• Compliance with FAA Advisory Circular 70/7460-IE, dtd. 11/1/76, "Obstruction Marking and Lighting"
Hazards to Public	
• Rotor Failure	• Safe Life Design • Structural Tests • Crack detection System-Shuts Down WTS
• Flying Ice	• Ice Detection System-Shuts Down WTS
• Unauthorized Entry	• Steel Door, Locked, and Auto Shut Down in Case of Unauthorized Entry
Hazards During Maintenance	• General Safety Design Features • Occupational Safety and Health Act of 1970 (Public Law 91-596) and applicable State Safety Regulations • MIL-STD-1472, Human Engineering Design Criteria for Military Systems, Equipment and Facilities • IEEE Standard 142-1972, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems • ANSI C2 American National Standard, National Electrical Safety Code, 1977 Edition • Maintenance Personnel Safety Features • Capability to remove person on stretcher • Fire detection and extinquishing system • Emergency exit doors and "Rescumatic" device to allow egress from either end of nacelle • Ability to lock rotor in horizontal and vertical positions (lock on high speed shaft) • Maintenance scenario and estimated O + M cost assume "buddy" system • Operations and maintenance manuals contain safety cautions

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Table 2-4. Availability Analysis

Item (Control number)	Number of system failures per year [1]	Mean time to repair (hours) [2]	Average annual outage hours		Availability
			Hours/year	% of total	
ROTOR					
Blades & hub	.82	68	55.8	22.0	.9937
Pitch control mechanism	2.11	11	23.2	9.1	.9974
Ice and crack detection	.29	17	4.9	1.9	.9994
DRIVE TRAIN					
Low speed shaft, bearings & electrical distribution	.83	69	57.3	22.5	.9935
Quill shaft & couplings	.15	48	7.2	2.8	.9992
Gearbox & gearbox sensors	.48	30	14.5	5.8	.9983
High speed shaft, couplings, rotor brake	.23	11	2.5	1.0	.9997
Lubrication system	[3]	–	–	–	–
Generator	.09	48	4.4	1.7	.9995
NACELLE					
Structure & wind indicators	.50	8	4.0	1.6	.9995
Yaw drive system	1.40	28	39.8	15.6	.9955
Electrical cables & slip rings	.36	9	3.2	1.3	.9996
Generator accessory unit	.77	7	5.2	2.0	.9994
TOWER					
Tower assembly	.10	8	.8	0.3	.9999
Electrical cables & equipment	1.06	7	7.4	2.9	.9992
Control subsystem	3.0	8	24.0	9.4	.9973
TOTALS	12.19	20.9	254.2	100	.971
50% of scheduled maintenance (from Maintenance Analysis)			36 hours		.967

[1] Includes application of 75% duty cycle where appropriate

[2] Includes all causes of downtime (Administrative delays plus hands-on time)

[3] Redundant system for gearbox. Sump system for low speed shaft and generator included in these subsystems.

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Detailed maintenance analysis has been performed to identify labor requirements, tools, and equipment. The demand frequency and repair time estimates for unscheduled fault maintenance of a mature unit are summarized in Table 2-5.

Maintenance tools and test equipment are discussed in Section 5.5.2. Total cost for this equipment is approximately $10,000 per wind turbine in a 25 unit farm.

A spares analysis was conducted to identify the initial inventory of spares for the 25 unit farm. Each spare requirement was established based on criteria that the cost to carry the spare(s) must be less than the penalty of lost electricity when waiting for the replacement part. This calculation includes the failure rate, reorder time, average power production rate, value of power, and the fixed charge rate on the initial investment. This analysis derived the estimated cost of initial spares inventory at $5,000 per unit for a 25 unit farm. This low value is based on a production scenario of 20 wind turbines per month where a central spares depot could support many farms of wind turbines.

2.6.3 Maintainability and Maintenance Concepts

The design goal of .96 availability can only be achieved if the system is highly maintainable. All MOD-2 drawings have been reviewed by a maintainability specialist to ensure ease of access and to enable each component to be removed and replaced or repaired in place. The major features incorporated to support maintenance are shown in Figure 2-28. The key elements of the maintenance concept for the 25 unit farm are summarized below:

- o Operations and Maintenance Manual defines scheduled and fault maintenance tasks.
- o Training for dedicated maintenance personnel.
- o Electrical/electronic and mechanical technicians.
- o Two shift coverage, 2 man crews, six days per week.
- o Additional support crews for major fault repair.
- o Use of outside services ´ r shop repairs, special tasks and heavy equipment rental.
- o On-site maintenance equipment - portable tools and fixtures for materials handling.
- o Utility depot spares availability - Electronics and small items in panel truck.

Table 2-5. Maintenance Analysis

	Number of unscheduled maintenance actions per year	Repair/inspect time (manhours per year)		Total annual maintenance manhours	
		Scheduled	Unscheduled	Manhours	% of total
ROTOR					
Blades & hub	.82	28.0	42.0	70.0	20.1
Pitch control mechanical	5.22	4.2	75.4	79.6	22.8
Ice and crack detection	.37	0.5	5.8	6.3	1.8
DRIVE TRAIN					
Low speed shaft, bearings & electrical distribution	1.16	7.0	36.4	43.4	12.4
Quill shaft & couplings	.15	–	4.8	4.8	1.4
Gearbox & gearbox sensors	.62	13.2	18.7	31.9	9.2
High speed shaft, couplings, rotor brake	.31	2.4	3.0	5.4	1.5
Lubrication system	.40	2.4	3.4	5.8	1.7
Generator	.09	–	2.8	2.8	.8
NACELLE					
Structure & wind indicators	.70	4.2 [1]	9.8	14.0	4.0
Yaw drive system	2.80	6.2	26.3	32.5	9.3
Environmental control system	.01	.3	.1	.4	.1
Electrical cables & slip rings	.36	1.0	2.4	3.4	1.0
Generator accessory unit	.77	–	4.3	4.3	1.2
Electrical facilities	10.50 [2]	–	3.1	3.1	.9
TOWER					
Tower subassembly	.11	2.6*	.7	3.3	1.0
Electrical cables, lightning protection & equipment	1.45	1.0	17.4	18.4	5.3
Control subsystem	3.2	–	19.2	19.2	5.5
TOTALS	29.04	73.0	275.6	348.6	100
	(18.54 excluding aircraft warning lights)				

[1] Includes application of 75% duty cycle where appropriate

[2] Primarily aircraft warning lights

* Excludes painting time which is accomplished at the same time that the rotor is painted

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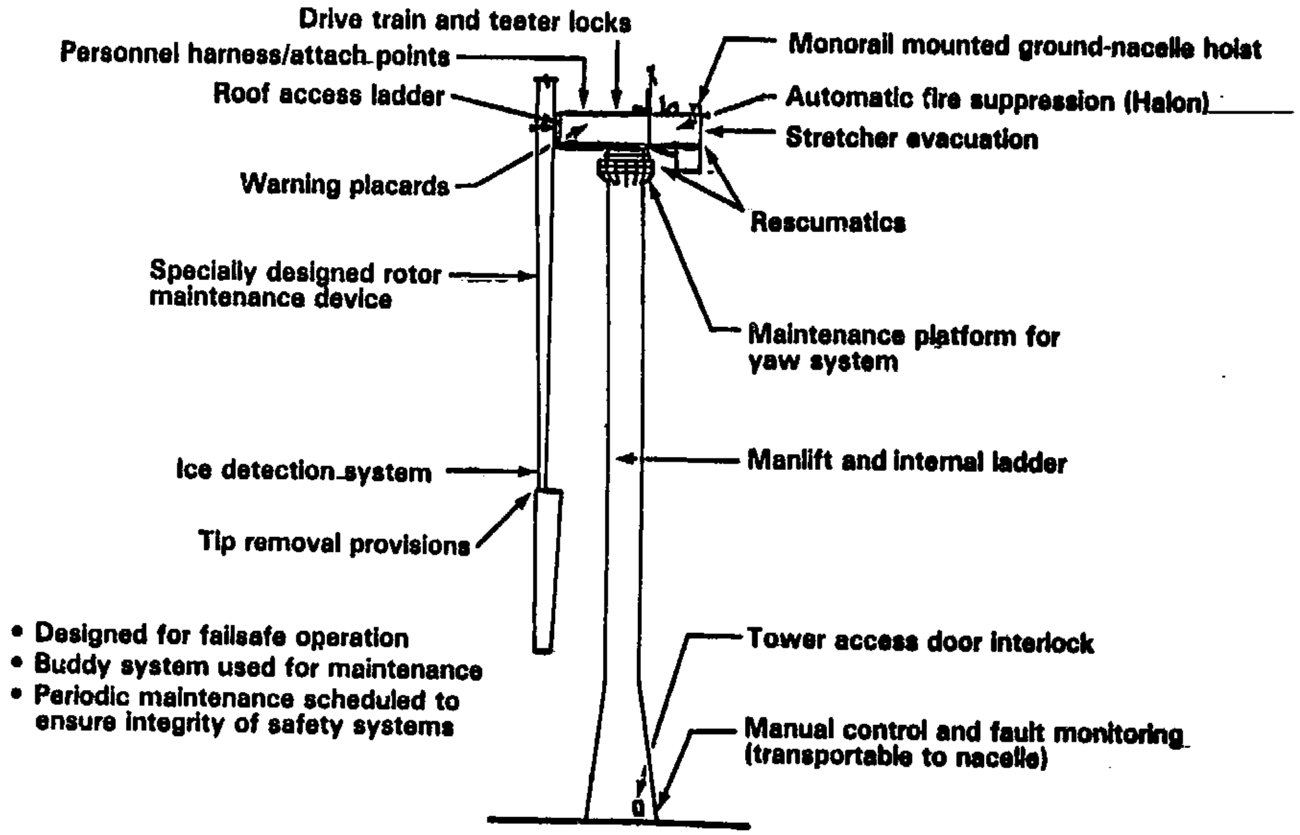

Figure 2-28. Operations, Maintenance and Safety Features

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2.7 FAILURE MODE AND EFFECTS ANALYSIS

The failure mode and effects analysis (FMEA) was initiated during preliminary design. The purpose of the FMEA is to identify all possible failure modes and to ensure that the resulting effects will not endanger personnel or cause damage to the wind turbine equipment. At the Detail Design Review, the documented FMEA was delivered to NASA and subsequently released as reference 2.

The component FMEA's were completed by the cognizant designers and reviewed by systems engineers and a reliability specialist. Failure rate data was incorporated. The major sources for the failure rate data were:

1. Non-electronic Reliability Notebook, Rome Air Development Center, January 1975, AD/A-0C5 657.

2. Reliability of Electrical Equipment in Industrial Plants, IEEG Survey.

3. Component Removal Data - 727, 737, 747 Commercial Aircraft, compiled by The Boeing Company.

4. Component Removal Data - 107 Helicopters.

5. RADC Reliability Notebook.

The "k" factors used to account for environmental differences were based on the following groundrules:

1. Rotor - equivalent to helicopter and "unmanned aircraft" environment.

2. Nacelle equipment - equivalent to "manned aircraft" environment.

3. Ground equipment - equivalent to "ground, stationary" environment.

An example of a completed FMEA worksheet is shown in Figure 2-29. The failure severity code is described in Table 2-6.

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MOD-2 Failure Mode and Effects Analysis

SUBSYSTEM	COMPONENT	PAGE
PITCH CHANGE MECHANISM	MOTOR-PUMP ASSY	18 FMEA NO: 4.3.1.7&8

FUNCTION OF COMPONENT

PROVIDE HYDRAULIC POWER FOR OPERATION OF PITCH CHANGE MECHANISM

FAILURE MODES & EFFECTS	APPLICABLE OPERATING MODES
1. LOW HYDRAULIC OR NO PRESSURE - PRODUCES LOW PRESSURE ALARM WTS SHUTDOWN	F,G,H
2. LOW HYDRAULIC FLOW - REDUCES PITCH CHANGE RATES, MOMENTARY LOW PRESSURE ALARM - WTS SHUTDOWN	F,G,H
3. EXCESSIVE HYDRAULIC PRESSURE - OVERHEATS HYDRAULIC FLUID. - WTS SHUTDOWN	F,G,H
4. LEAKS - EXTERNAL	F G H

FAILURE FREQUENCY			MEAN TIME BETWEEN FAILURE (YEARS)	FAILURE SEVERITY			
FAILURE MODE NO.	FAILURE MODE FREQ. %	COMPONENT FAILURE RATE x 10^6 PER HOUR		MINIMAL I	MARGINAL II	CRITICAL III	CATASTROPHIC IV
1	50	38	6.1			X	
2	20	38	15.2			X	
3	100	17	6.7			X	
4	30	38	10.0			X	

FAILURE DETECTION METHODS

1 LOW PRESSURE ALARM - WTS SHUTDOWN

2 LOW PRESSURE ALARM - WTS SHUTDOWN 4 - LOW LEVEL ALARM - WTS SHUTDOWN

3. OVERHEAT ALARM - WTS SHUTDOWN

DISCUSSION AND CORRECTIVE ACTION (IF APPLICABLE)

NAME D. W. KING DATE 8/9/78

Rev. 10/25/78

OPERATING MODES

A - SHUTDOWN	D - TRANSITION TO STANDBY	G - OPERATE
B - TRANSITION TO WARM-UP	E - STANDBY	H - TRANSITION TO FEATHER
C - WARM-UP	F - TRANSITION TO OPERATE	I - FEATHER

78-K-6162-001

Figure 2-29. Example of FMEA Worksheet

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This analysis of FMEA provided a disciplined method of developing the failsafe protective systems. Figure 2-30 depicts this approach. In general, redundant load paths for major structural components were not economically feasible, so a safelife design concept is employed. That is, a conservative spectrum of 30 years blade cyclic loading, with a conservative allowable flaw size was used to develop the fatigue stress allowables used to design for 30 year life. In addition, periodic inspection is defined and a crack detection system as described in Section 2.2.1 provides warning of crack development and system shutdown prior to a crack growth to the critical failure length. The electrical/mechanical systems provide redundancy where appropriate and protective sensors to initiate a microprocessor controlled safe shutdown for operating parameters outside of a safe tolerance. Critical failure modes are identified which require a "fast" shutdown (i.e. high tip blade pitch rate using the emergency accumulators). Also, certain critical paramaters trigger a backup failsafe control system which is independent of the microprocessor control system. The most critical parameter of rpm overspeed also triggers a third independent emergency shutdown system. Parameters critical to generator protection also provide for opening of the generator circuit breaker. The critical parameters and their safety shutdown systems are shown in Figure 2-22.

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Table 2-6. FMEA Safety and Failure Severity Categories

Hazard category	Impact			
	Function	Repair cost	Time to repair	Personnel injury
Minimal	None [1]	and Under $1,000	and Under 2 days	and None
Marginal	None critical [2]	and Under $1,000	and Under 2 days	and First aid
Critical	Loss of function [3]	or Up to $10,000	or Up to 10 Days	or Hospital
Catastrophic	Loss of system [4]	or Over $10,000	or Over 10 days	or Fatal or permanent disable

[1] Minor items that can be repaired with convenience.

[2] No loss of generating capability, but repair must be accomplished within 2 weeks to avoid shutdown.

[3] Causes WTS shutdown.

[4] Destruction of major element such as rotor or gear box.

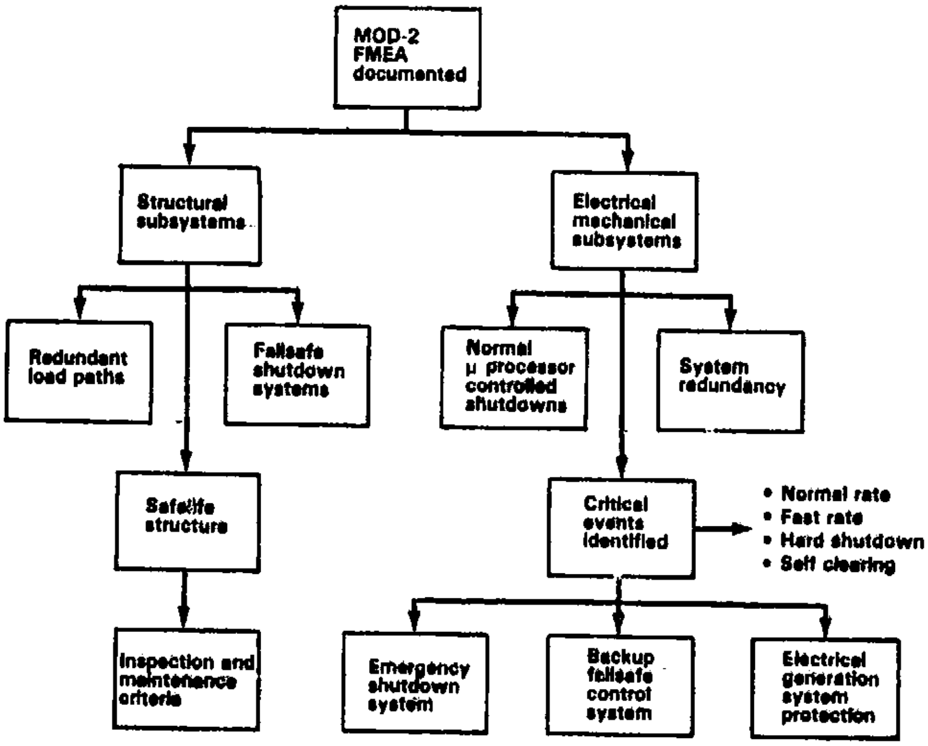

Figure 2-30. Failsafe Protective System Development

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In summary, the FMEA's identified nearly 1,000 failure modes and corrective actions were implemented to preclude costly failures. Table 2-7 summarizes the protective approach to major failure modes. Needless to say, the overspeed incident to WTS #1 brought about a comprehensive review of FMEA and instigated several corrective system hard ire and software changes.

Table 2-7. FMEA Summary

Failure mode	Effect	Potential corrective action
Structural failures		
Rotor		
• Blade Fatigue cracks • Spar buckling • Fatigue crack at control tip spindle and thread or at tip-blade inter-face • Inboard joint-rotor to hub bolt or flange weld failure • Broken teeter trunnion or flange cracks • Buckling inboard sections or hub compression skins	Loss of part of rotor and possible secondary damage if allowed to progress	• Safe life design • Fatigue tests • Inspection schedule • Possible crack detection system • Mid-blade assembly buckling test
Drive		
• Broken low speed shaft, • Broken quill shaft bulkhead joint	Loss of load emergency shutdown effected prior to reaching damaging over-speed (see memo K-6265-SS-487, DTD, 18 Oct, 1978)	• Safe life design
• Teeter shaft or flange cracks	Possible rotor loss	• Strain gage correlation
Tower		• Safe life design
• Failure of structure or foundation	Could initiate collapse	• Safe life design
Control system failures		
• Signal to one tip incor-rectly drives control surface to zero pitch • Control linkage to one tip jams	Emergency shutdown triggered by differential of tip position signals. Shutdown occurs prior to damaging overspeed	None required, analysis verifies that one tip operative can safely stop rotor (see memo K-6265-SS-487, DTD 18 Oct. 1978)
• Control system signal to both pitch actuators incorrectly drives control surfaces to zero pitch	Emergency shutdown triggered by generator output power sensor. Shutdown occurs prior to damaging overspeed	None required
• Power output sensor fails, calling for power increase when system is already at full power output	Damaging overspeed possible if load drops off prior to initiating shutdown	System changed to command shutdown prior to load dropping off. Also, back-up power sensor signal sent to controller
Electrical power failures		
• Synchronizer provides signal to close bus tie contactor too soon or too late (WTS not proper phase relationship or voltage to mate with bus)	High current transient causing high torque load on the generator that could cause mechanical damage to generator or drive train	Synchronizer is fully redundant and fail safe
• Loss of commercial power while WTS is at rated power	Shutdown occurs prior to damaging overspeed	None required, see memo K-6265-SS 487, DTD 18 Oct. 1978

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3.0 TESTING

Development of the MOD-2 WTS has required considerable testing to establish design criteria, provide data for checkout and acceptance, and establish turbine performance. This testing is discussed in the following sections.

3.1 DEVELOPMENTAL TESTS

Development tests were conducted to verify static strength, fatigue and operational characteristics of components to meet a 30 year life requirement. The following sections describe the component tests, test results and their impact on component design for these tests not discussed fully in References 1 and 5.

3.1.1 Crack Detection

The crack detection system incorporated in the MOD-2 was designed to detect through-thickness cracks in the rotor blade and shut the wind turbine system down prior to catastrophic failure of the rotor. The system pumps warm dry air through the blade interior and dumps the air overboard at the inboard end through an orifice. The flow through each blade orifice is monitored, and the difference between blade flows is an indication of the existence of another exhausting orifice, which could indicate a through-crack. The determination of the minimum length crack which could be detected was estimated using design parameters, for flow through a given sharp-edge orifice. However, the flow through a crack-like orifice is at best difficult to predict, especially under the time varying state of stress in the structure. To minimize false alarms, the critical leakage rate should be reasonably high, yet low enough to provide a comfortable margin between detection and structural failure. Fracture toughness testing was required to provide the data necessary for assessing the critical crack length for the MOD-2 blade material, for which toughness has been assumed as being 125 ksi in.

3.1.1.1 Operational Test

A test was conducted to verify that the MOD-2 crack detection system possessed adequate sensitivity and stability to detect a given crack in one rotor blade as well as to detect malfunction of the system. Two 12,500 gallon tanks were used to simulate the air volume of the two rotor blades. Cracks in the blades were simulated by use of a manual valve and flowmeter on each blade simulator. The wind turbine crack detection system was located indoors and was connected to the blade simulator tanks located out of doors.

During testing of the crack detection system, it was found that the blade orifice tubes had to be shortened in order to increase the air flow and thus increase the sensitivity of the system to air flow imbalance between blades. The system was able to detect malfunctions such as blower failure or air blockage. A 2 psi over-pressure relief valve was incorporated to prevent over pressuring the blades, and a check valve was added to the dehumidifier outlet. The ability of the system to deliver dry air to the blades was confirmed. A system calibration procedure was established.

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3.1.1.2 Crack Air Flow Test

A crack flow test program was carried out on pre-cracked specimens .25 inch and .50 inch thick. The objective of the program was to experimentally develop a means of determining air flow rate through a crack in a rotor blade under varying stress, pressure differential across the crack, and plate thickness for different crack lengths. Each specimen became the closeout panel of a rectangular flow chamber in which the pressure was varied by varying the inlet flow rate. Cracks of 9 inches and 12 inches were tested on the thicker panel, and cracks of 12, 18, and 24 inches were tested on the thinner panel. The test panels were clamped to the edges of the flow chamber so that the application of end loads on the specimen would produce uniform stress across the uncracked portions of the specimen. Gross area stresses were varied up to 9 ksi and flow pressures (pressure differential across the crack) ranged up to 4 psi.

The state of stress affected the crack opening and thus the mass flow through the crack. The results of the testing indicated that the mass flow through a crack would follow the relationship:

$$m = 2.7 \times 10^{-3} (t)^{-.25} (\sigma)^{1.65} (a)^{1.90} (p)^{.5}$$

where m = flow in (CFM)
t = thickness (in)
a = 1/2 total crack length (in)
p = Pressure differential across thickening (psi)
σ = stress (ksi)

3.1.1.3 Fracture Toughness Test

The fracture toughness tests were conducted on two pre-cracked specimens fabricated from .25 inch and .50 inch thick ASTM-A572 grade 50 material to verify that the toughness was greater than 125 ksi in. as assumed. The width of each specimen was 60 inches while the pre-crack was 24 inches long. The specimens were sized to give "valid" data up to 125 ksi in. and conservative results above 125 ksi in. The criteria for "valid" data was: 1) a net section stress less than 80% of yield, 2) an initial crack length less than 40% of the specimen width, and 3) a gross area stress less than 18 ksi (the maximum design stress in the rotor). To obtain valid plane strain fracture toughness data would require specimens better than 22 inches thick; these would not be representative of the MOD-2 structure. Each specimen was instrumented with crack propagation gages on the same side of the specimen in a manner such that a stable crack growth of 4.8 inches could be monitored.

The thicknesses selected for testing were representative of those used in 80 percent of the rotor but less than the 1.0 inch employed out to Station 90. Experimental limitations precluded the testing of 1.00 inch plate. The material used was not desulphurized as the rotor material was and also had a higher minimum yield strength than the rotor material. The material substitution was necessary because the proper material was not available. Both the lack of desulphurizing and higher strength would tend to decrease the fracture toughness of the material.

During testing, the center portion of the specimen was enclosed in a styrofoam box which acted as a cryostat. Thus the test portions of the specimen was maintained at a temperature of -40°F, the minimum operating temperature for the wind turbine. The test load was applied at a rate such that a stress intensity of 125 ksi in. would be reached in 30 seconds. The .25 inch thick specimen failed at a net area stress of 55 ksi, which was greater than the guaranteed yield strength of 50 ksi. The material toughness was well in excess of 225 ksi in. The .50 inch thick specimen failed at a net area stress of 46.2 ksi and an apparent toughness of 188 ksi in. Neither specimen satisfied the criteria for "valid" data because they both failed at too high a stress. It is apparent from the data that fracture toughness of the rotor structure is well in excess of 125 ksi in.

3.1.1.3 Crack Detection System Evaluation

The mass flow operation developed in the crack flow test and the fracture toughness results were used to evaluate the ability of the crack detection system to detect cracks prior to reaching critical length. Figure 3-1 shows the relationship of crack flow, as a ratio of detectable flow rate, to the number of hours a detectable crack becomes critical. The relationship is for the blade station 360 which has the minimum time before a detactable crack becomes critical.

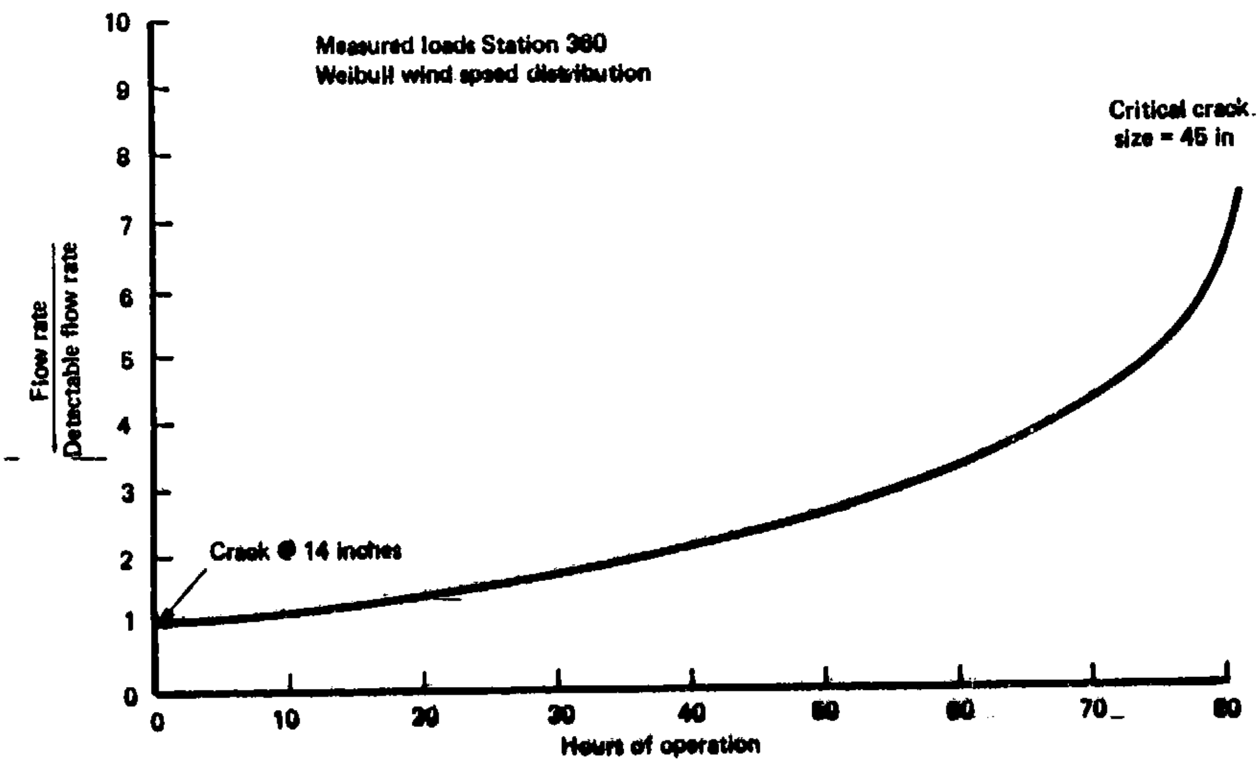

Figure 3-1. Crack Detection System Capability for Blade Station 360

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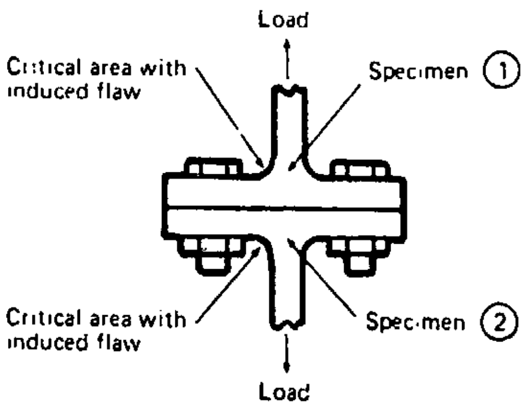
3.1.2 Rotor Rib Field Joint

The MOD-2 rotor blade has a field assembly splice at blade radial station 360 which attaches the blade mid-section to the hub through ribs that are welded to both skins and spars. The bolt attachment is symmetric about skin and spar. The joint is highly stressed under fatigue loading, and a test program was conducted to validate the joint for MOD-2 design. The results of this test provided additional substantiation for the crack growth model discussed under material testing.

The testing was carried out using an MTS (Material Testing System) test machine under the design fatigue spectrum of loads for the joint. The results shown in Figure 3-2 indicate good correlation was obtained between predictions and test results. The fatigue analytical model was validated and was used to design the field joint.



Test Data

	1	2
• Fillet area stress (psi)	18,000	18,200
• Initial flaw length (in)	0.248	0.234
• Predicted fatigue life	17,000,000 cycles	17,000,000 cycles
• Test specimen life	18,953,754 cycles	21,151,277 cycles

Figure 3-2. Rotor Blade Field Joint Test

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3.1.3 Rotor Spindle

The spindle test program was performed to substantiate the structural integrity of the rotor blade spindle and its supporting structure. The design requirement to rotate the blade tip section resulted in complex structural load paths surrounding a spindle bearing structure. A complex finite element stress analysis was performed to evaluate this structure.

The test program objectives were:

(a) To validate the analytical means for predicting the deflection and internal stresses of the spindle and supporting structure.

(b) To define the areas of high local stresses in the spindle and supporting structure, which occur during normal operating conditions of the wind turbine.

(c) Validate the operation of the pitch control system

The tests were performed by mounting the spindle section of the blades in a cantilevered position and applying combinations of flapwise and chordwise loads selected to produce one full life of fatigue damage on both the upper and lower blade surfaces. The test specimen include all blade structure between spanwise stations 1140 and 1360. The pitch actuator and supporting hydraulics were also included. Specimen test loads were imposed by a series of hydraulic actuators connected to the outboard end of the specimen through a rigid adapter fitting. A schematic of the test setup and the loads are shown in Figure 3-3.

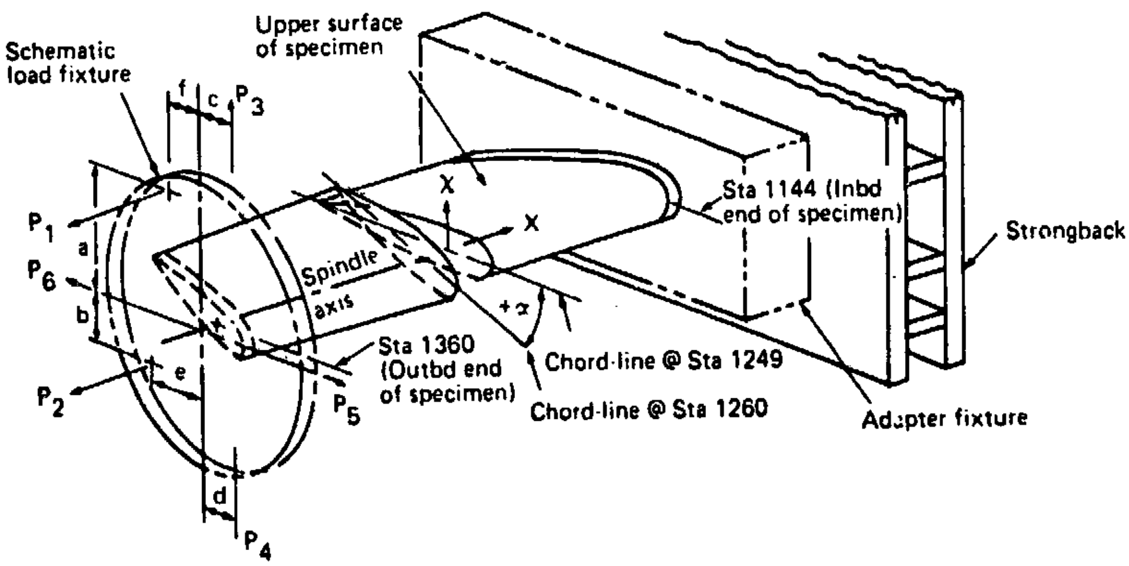

Figure 3-3. Schematic of Spindle Fatigue Test Set-up

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Strain, deflection and applied loading data were recorded for all test conditions. The instrumentation consisted of 73 strain gages, 12 deflection transducers, 7 load cells, and one angular potentiometer.

All test objectives were achieved. The 30 year design life was demonstrated and good correlation was obtained between predicted and measured stresses. The areas of high local stress were identified by analysis and confirmed by test (Figure 3-4). No additional high stress areas were detected, and all margins of safety in the critical areas were equal to or greater than predicted. (Predicted values in () in Figure 3-4).

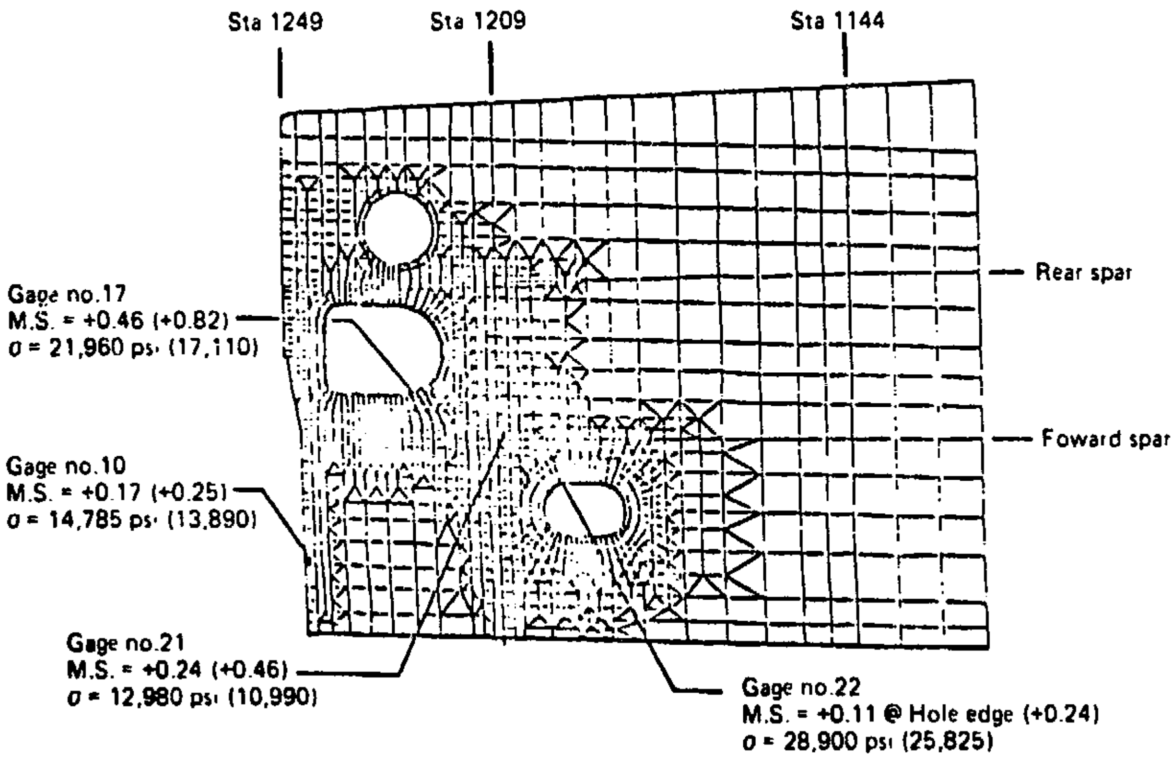

Figure 3-4. Margins of Safety at Critical Locations of Test Specimen

3.1.4 Pitch Control Testing

Pitch control system testing included the use of the spindle fatigue test specimen as a means to functionally test the hydraulic swivel in the blade-tip pitch control system. The swivel is that portion of the hydraulic supply that provides the connection between the fixed portion of the blade at station 1249 and the tip actuator. The swivelling motion is from a tip position of -5° to +94°. The testing of the swivelling joint included simulated startup, operate, and shutdown blade-tip pitch action as well as dithering for extended period of time. During the spindle fatigue test, the control system was active and was used to pitch the tip section to operating or critical shutdown load positions (5° or +28°). It was also used to maintain a given pitch position of the tip during the imposition of the time varying test loads. The control system held the pitch position to ± .1° under load application, thereby validating its design stiffness.

In order to develop and check out proposed changes in the pitch control system, open and closed loop frequency response tests were performed on the cyclic load test hardware. The test hardware provided the proper pitch actuator hydraulics and simulated tip rotary inertia. The objectives of the test were to evaluate proposed changes and optimize control system parameters to guarantee a 1 hz frequency response and demonstrate required stability margins. Various control system changes were evaluated on a patch board to arrive at an improved control system.

Computer simulation of the control system had demonstrated that frequency response must exhibit a gain of -30 dB to +9 dB at 1 hz and outer loop stability requires a gain of at least -5dB at 180 degrees phase shift. The transfer function data obtained from the improved pitch control system of the cyclic load test specimen satisfied these requirements. Hardware and software modifications were later implemented and optimized during system integration testing.

3.1.5 Teeter Bearing

The rotor is connected to the drive shafting through a teeter hinge and its elastomeric radially (teeter) and axially (thrust) loaded bearings. The radial bearings react rotor thrust, rotor driving torque, and rotor dead weight loads. The axial bearings are basically to react rotor dead weight when the rotor is approximately horizontal, as well as lateral components of rotor thrust.

3.1.5.1 Qualification Testing

The first elastomeric teeter bearing was subjected to qualification tests by the manufacturer in order to assure bond quality and to obtain performance data.

The soundness of the bonds between rubber and steel shims as well as between rubber and hub structure was verified by rotating the inner hub +15° relative to the outer ring structure. The angular motion was 2.3 times the expected extremes of travel during bearing operation (±6 1/2°). The torsional stiffness of the teeter bearing was ascertained at -40°F as well as at room temperature. The results of the stiffness tests indicated compliance with bearing design specifications.

3.1.5.2 Fatigue Testing

The teeter bearings had been designed with methodology developed for much smaller bearings used in the helicopter industry, and those used in the oil industry that require application of low stress low motion design. Because of lack of test data and experience on bearings of the MOD-2 size, as well as the fact that the life requirement was well beyond even helicopter experience, it was decided that a fatigue test was required. In addition, this test provided data for maintenance and inspection procedures. Spectrum testing for the 200 x 10^6 cycle equivalent of the 30 year design life would be out of the question since the operating rotational frequency is 17.5 cpm. A review of the operating loads and teeter angle spectrum indicated that, bearing testing with applied loads of rated drive torque loads in combination with a time varying rotor weight load, as well as a rotation to maximum teeter angle (±6.5° to the teeter stops) applied for 2 x 106 cycles would expose the bearing to an equivalent 30 year life. The test bearing was instrumented with strain gages, thermocouples, load and displacment transducers.

Throughout the test, the radial spring rate did not vary at all, and the torsional spring rate had reduced 7% by the end of the test, well below the 20% failure criterion set by the bearing supplier. Stabilized temperatures in the rubber were approximately 150°F without fan cooling, and 135°F with cooling. Design operating temperatures will be well below the no-fan cooling temperature because design operating teeter angles are of the order of ±2 to ±2 1/2°, not the ±6 1/2° continuous oscillation sustained during the bearing fatigue test. Testing was terminated at 1.8 * 106 cycles due to cost and schedule contraints. There was no indication of problems which would significantly alter the test results if the remaining 0.2 * 106 cycles were run.

3.1.6 Gearbox, Back-to-Back Test

3.1.6.1 Fatigue Testing

The epicyclic gearbox selected for the MOD-2 utilized an existing design concept but its torgue transmitting capability was improved by 200% and its new design life was 30 years. Because the capabilities extension was beyond the current state-of-the-art, a qualification test was deemed necessary to verify predicted performance parameters.

The selected test method was a back-to-back test in which two complete gearboxes and their lubrication systems would be connected in order to impose the high input torques of the operating wind turbine. The high speed output shafts were connected with a torsion bar, while the torque reactions were through the low speed shaft flanges, as both low speed shaft flanges were tied together. The torsion bar preload was varied throughout the test to provide simulated drive line power variations in operation. A drive motor was connected to the output shaft of one of the gearboxes, providing the rotational speed control. The gears of one of the boxes were strain gaged to monitor the tooth stresses throughout the program.

A spectrum of operating conditions was simulated in the test program during which it was determined that gear tooth bending stresses were well below AGMA predictions. Slight modifications to the first stage helical gears' lead correction angle had to be made. It should be noted that had a full load test not been conducted, such a deficiency would have gone unnoticed. Direct measurements of gear train efficiency, gearbox breakaway torque, noise levels and vibration characteristics were made throughout the test.

As a result of the back-to-back test program, the fatigue rating of the gearbox was substantiated up to 155% of design rated torque.

3.1.6.2 Vibration Survey

When running the gearbox at zero torque during the back-to-back load test, a rapid buildup of horizontal vibration at 1400 output rpm was experienced. The system ran smoothly up to 1800 rpm with the application of only 15% of rated torque. It was determined that the gearbox third stage planet passage frequency was resonant with the test stand yaw-lateral natural frequency. At low torque levels, the third stage planets and sun of this gearbox are free to move off their rotating center, causing unbalance at the planet passage frequency.

The gearbox mount lateral stiffness was determined from subsequent tests. Analysis of the gearbox as installed in the MOD-2 nacelle predicted natural frequencies well in excess of 2600 rpm. Therefore no mount vibration problem at planet passage frequency was expected. This was subsequently confirmed in integration testing of the installed gearbox.

3.1.7 Modal Survey

Modal survey testing of wind turbine systems and their components is an important part of the design and testing process. The modal survey is an effective way to ensure that the wind turbine subsystems meet performance expectations. After evaluating alternative testing techniques, it was concluded that the MOD-2 modal survey would be conducted with the rotor and nacelle installed on the tower in the operational configuration. The advantages were that the system modes and damping would be measured directly, including all coupling mechanisms which were hard to model.

The testing approach selected involved the use of a HP 5451B Modal Analysis System (similar to the one used for the modal analysis of MOD-0). The test technique involved impacting the wind turbine at a prescribed point with a 1,000 lb. instrumented ram and recording the response of fixed accelerometers. The overall technique is based on the use of digital processing and the Fast Fourier Transform (FFT) to obtain transfer functions data and then use of a least-squared error estimator to identify modal properties from the transfer function data.

A specially designed 1,000 lb. ram was instrumented with a force transducer in its head. The ram was swung from the gin pole used for MOD-2 erection and allowed to impact one blade tip. To ensure proper impact, the ram was constrained to follow a cable through the center of the target disc.

The impact force must be of sufficient magnitude and duration to excite the significant modes of interest. The ram was calibrated before the modal survey by varying the stiffness of the ram impact head (interchangeable foam rubber pads) and varying the swing length to develop approximately 1,000 lb. with 200 ms duration.

The modal frequencies and damping results of the modal survey are shown in Table 3-1. The data are a direct output of the HP 5451B Fourier analyze systems with the exception of chordwise bending, nacelle pitch and drivetrain torsion modes which were determined by supplemental analysis.

The data gathered during the MOD-2 modal survey tests verified the achievement of required system design frequencies. In particular, the drive train, tower and blade modes were identified and shown to meet system frequency placement and separation requirements. The measured damping provided assurance that design damping assumptions were reasonable.

Table 3-1. Model Survey Results

MODE	FREQUENCY (Per revolution) PRED.	FREQUENCY (Per revolution) MEAS. [1]	DAMPING (%) MEAS.
Teeter	0.14	----	----
Drive Train Torsion	0.46	0.45	----
Tower Bending Fore/Aft	1.24	1.23	1.0
Tower Bending Lateral	1.27	1.28	4.2
Flap Bending Sym.	3.09	3.30	0.35
Chord Bending Sym.	6.22	6.17	----
Flap Bending Antisym.	6.45	6.55	1.04
Flap Bending 2nd Sym.	7.71	9.6	0.78
Nacelle Pitch [2]		8.23	

[1] Measured with test box beam fixtures on tips
[2] Supplemental data

3.2 INTEGRATION TESTS

Integration testing is that system and subsystem level testing conducted on each wind turbine system prior to initial operation under wind power. Figure 3.5 shows a test flow diagram for the -100 Integration Tests on units #1, #2 and #3.

3.2.1 Integration Test at Pocatello Unit #1

For unit #1, a series of tests were performed on the assembled nacelle while installed on a test stub tower section and with a rotor simulator. This testing was conducted in July and August of 1980 at the facilities of the M&E contractor Bucyrus Erie, in Pocatello, Idaho.

3.2.1.1 Electrical Continuity (-101)

This test performed a power-off point-to-point continuity check of operational wiring in the nacelle and the test set up at Pocatello.

3.2.1.2 EIS/MDS/WTS Interface (-102)

This test performed a checkout of the Engineering Instrumentation System (EIS) on the nacelle and to the Mobile Data System (MDS) van. It included continuity checks as well as power on tests.

3.2.1.3 NCU Stand Alone (-103)

This test performed a verification that the NCU was assembled properly and ready for integration with the nacelle. A separate 48 vdc power supply was used and the interface with the sensors was simulated by the Field Test Unit (FTU).

3.2.1.4 Nacelle Integration Test (-104)

The general objective of these tests was to gain experience with and verify functional operation of, as much of the WTS equipment as possible before shipment to the field site.

The test was divided into 8 sub tests.

- -1 Gearbox Lube System checkout
- -2 Control System checkout
- -3 Drive train checkout
- -4 Crack Detection System checkout
- -5 Rotor Simulator and Pitch System checkout
- -6 Yaw System checkout
- -7 System Test and 72/12 Hour Drive Train test
- -8 Fire Control System checkout

A summary of the results are as follows:

-1 Gearbox Lube System Checkout

Manual operation of the lube system from the A200 panel was performed satisfactorily. The test identified a problem with the dehumidifier motor bearings; a design change has corrected this. Checks of the oil reservoir heater operation revealed the need for a protective cover over each heater control unit; a design change incorporated a cover. Checks of the circulating pump and each lube pump were satisfactory; the pump relief valve required adjustment to provide maximum system pressure. Adjustment of the lube oil temperature regulator was performed subsequent to the 72 hour drive train test. Normal operation of the built-in instrumentation and the active engineering instrumentation was verified. Several oil leaks in the lube oil module were found and corrected; these were associated with improper assembly.

-2 Control System Checkout

R.

Checks of the RPM sensors were made and showed several problems; they included chain misalignment, wrong sprocket size, and failsafe system triggered NCU immediately on motion. Changes were initiated and temporary fixes incorporated to allow the test to proceed. Calibration of the blade position potentiometers (mounted on the rotor simulator) revealed servo valve biases, incorrect servo valve output scaling and grounding and wiring problems. These were subsequently corrected. Checks of the wind sensors and the vibration sensor were satisfactory though a modification the vibration sensor circuit was identified.

-3 Drive Train Checkout

The generator was direct coupled to a DC controlled motor and driven over the range 300-1980 rpm. A GAU phase C potential transformer fuse was found blown during initial checks, however when this was replaced, verification of phase rotation and voltage regulator settings were accomplished. Checks of the active engineering instrumentation system were satisfactory. Generator vibration levels were within specification and no nacelle modes were identified that would compromise generator performance or reduce life.

The gearbox and low speed shaft were also driven over the range 300-1980 rpm using a DC controlled motor coupled to the aft end of the gearbox. Checks of the active engineering instrumentation and the gearbox lube system during rotation were made. Vibration levels were satisfactory at the gearbox and low speed shaft bearings; no unacceptable resonances were identified and functional operation of the gearbox and low speed shaft appeared satisfactory. A substantial oil leak from the rear seal of the gearbox was identified and action initiated to provide a revised seal that corrected the leak.

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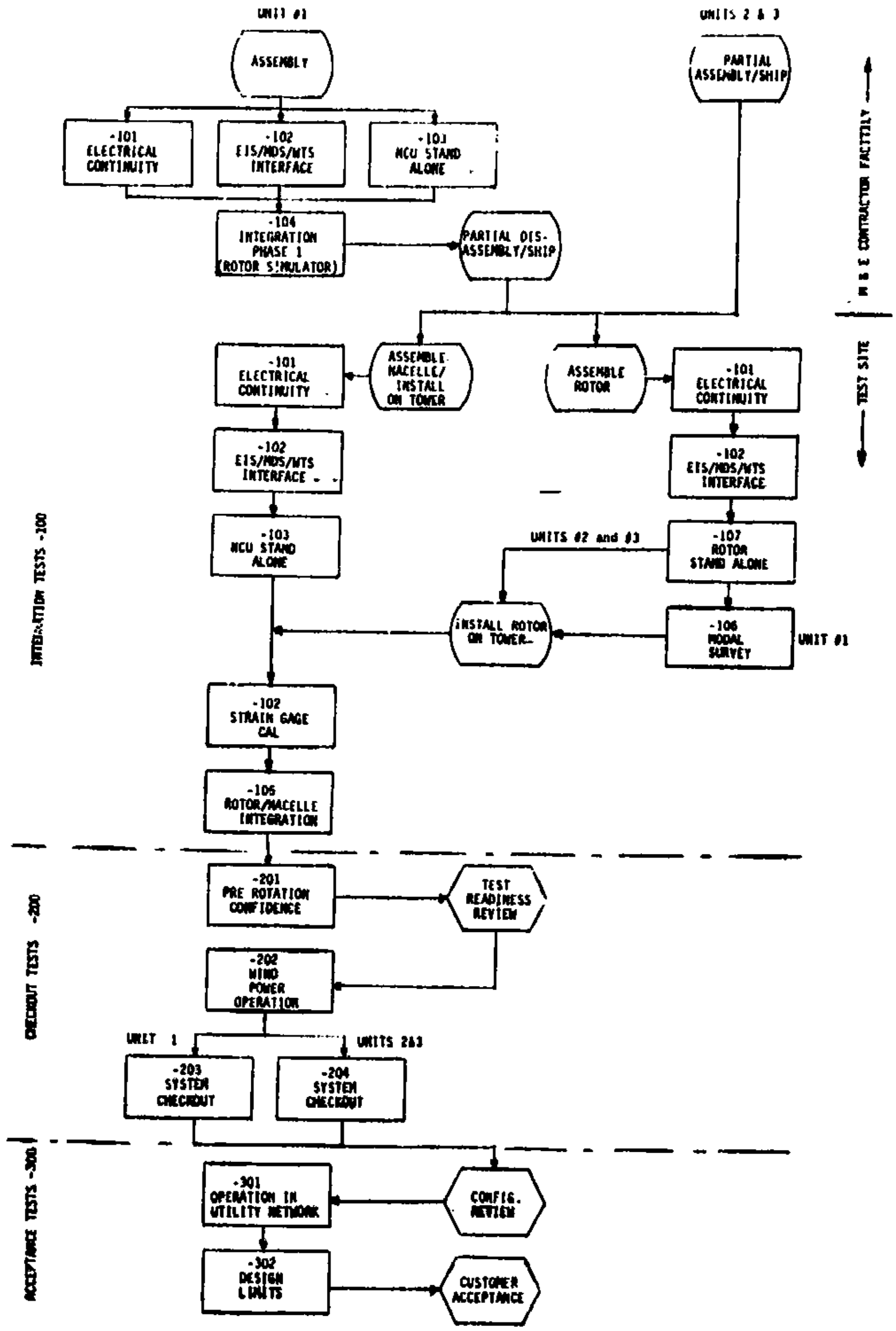

Figure 3-5. WTS Test Flow

-4 Crack Detection System Checkout

Checks included, normal flow, high flow and low flow for each blade. All tests were satisfactory with LSS stationary and with rotating at 17.5 rpm.

-5 Rotor Simulator and Pitch System Checkout

Checks completed satisfactorily included NCU command of pitch position, teeter brake release at 7.8 rpm, startup times under different wind speeds, response to rate commands, pitch pump pressure capability, emergency shutdown commands, 1 hz response characteristics under rate command, and operation of active engineering instrumentation. Performance that was not verified included blade tracking during rate commands and emergency feathering, and startup pitch schedule. Workarounds were used to allow testing to proceed and changes in the system configuration were initiated. Deferred tests were planned for conduct in the field prior to erection of the nacelle. Data from this test resulted in new servo valves and counter-balance valves being used in the rotor manifold and changes in the NCU software to improve closed loop operation.

-6 Yaw System Checkout

All manual controls from the HPU were verified. The yaw rate was adjusted, however a non-smooth rotation was attributed to the flow control valves being too large. Smaller valves were installed and operation was satisfactory. Yaw brake operation functioned correctly however the system pressure drop caused an NCU trip. Software modifications were incorporated to correct this fault as well as a similar problem with the rotor brake operation. Yaw drag brake operation was verified. The yaw system operation was verified for yaw errors of less than 7°, 7° to 20° and greater than 20°. Rotor brake operation was satisfactory, however a frequent charging cycle to keep the brake disengaged was found to be due to a design problem; a subsequent design change corrected the problem.

-7 System Test and 72/12 Hour Drive Train Test

Verification of automatic mode features of the control system were completed using a field test unit for certain simulated inputs. These included an automatic startup, demonstrating wind inputs, yawing, pitch and lube system pump operation, breakaway, rotor brake release, operate mode, field and sync enable and bus tie contactor closing signals. This test showed that blade angles changed properly as a function of power output and that the system shuts down for low power. Startups in low and medium winds were verified; startup in high wind conditions was not possible due to a servo valve bias problem. Automatic shutdowns were demonstrated for excessive blade angles, loss of utility intertie, loss of one blade tip, excessive power output fluctuation and overspeed. Automatic startups with live wind was demonstrated. More than 67 hours of operating time was completed on the rotating system including more than 12 hours of continuous operation. One objective not met was verification of a normal shutdown (due to pitch hydraulic problems, see -5 test); this test was deferred to the field.

-8 Fire Control Checkout

This test verified operation of two smoke detectors, audible alarm, zone alarm light, automatic shutdown of the NCU and exhaust fans, and energizing of Halon bottle. All tests were satisfactory.

3.2.2 Integration Tests at Goldendale Units #1, #2, and #3

A series of integration tests were conducted on each unit at the test site at Goldendale prior to wind powered rotation (see Figure 3-5).

3.2.2.1 Electrical Continuity (-101)

This test performed a power-off point-to-point continuity check of operational wiring in the nacelle, rotor, tower and base facility. For unit #1 nacelle, this test only examined that wiring which was new or had been disturbed since the integration testing at Pocatello.

3.2.2.3 NCU Stand Alone (-103)

This test performed verification that the NCU was assembled properly and ready for integration with the nacelle. The test was performed with an independent 48V power supply and used the FTU and breakout box. This test was a repeat of a test performed in Pocatello, with revised software as a result of the experience gained in Pocatello. All hardware performed satisfactorily.

3.2.2.4 Rotor Stand Alone (-107)

This test performed a functional check of the fully assembled rotor hydraulics using a test hydraulic cart and a servo valve test control box. The ice detectors were tested for aliveness and the rotor was pressurized to verify its leakage rate compatibility with the crack detection system. The blade tip position potentiometers were adjusted with the tips in the faired position. The hydraulic checks and ice detection tests were performed successfully. The crack detection tests identified numerous leaks that were patched successfully.

3.2.2.5 Rotor/Nacelle Integration (-105)

This test was conducted with the nacelle and rotor installed on top of the tower. It verified that leakage rates of each blade were within tolerance and set the comparator pressure switches on the crack detect system. It confirmed that the ice detector circuit was alive. It set the pitch system servo loop gain and bias, and performed a frequency response test on each blade. A manual pitch test was run in position; rate modes, emergency feathering and teeter brake operation was checked. A manual rotate test (to 8 rpm) was run. This test also performed a demonstration of the yaw system including starting, running and stopping.

3.2.2.6 Modal Survey (-106)

For unit #1 only, a modal survey was conducted on the completed unit at Goldendale. This measured modal frequencies, damping and mode shapes as discussed in Section 3.1.7.

3.3 CHECKOUT TESTS

Checkout testing is that system testing conducted on each WTS to show it functions correctly and is ready for acceptance testing. Figure 3-5 shows a test flow diagram for the -200 checkout tests.

All checkout tests were conducted at Goldendale with the wind turbine fully assembled. These tests include a prerotational confidence test, a wind powered operation test and a system checkout test.

3.3.1 Prerotational Confidence Test (-201)

Prior to wind powered operation, a series of checks were made to assure manual control functions and failsafe protection were performing properly. The tests selected to give the most confidence in system integrity were, emergency feather operation, rotor brake/yaw brake operation, test van not-ready control, gearbox over temperature response, overspeed response and excess vibration response. Some of these tests required special configuration of the system to allow the test to be conducted since the system has automatic safeguards that would prevent test conduct. All tests passed successfully except vibration response; this problem was attributed to a bad circuit in the NCU. Since the EIS also monitored the vibration levels, this did not hold up the test.

3.3.2 Wind Power Rotation Test (-202)

This test was divided into three phases; 8 rpm manual control check; 17.5 rpm automatic control without synchronization and 17.5 rpm automatic control with synchronization at below and above rated power.

The 8 rpm test covered startups, yaw direction error, rotor brake operation, teeter brake operation, sustained rotation of 8 rpm, disc plane adjustment and teeter activity. The 17.5 rpm test, offline covered startup through the tower resonance range, speed control at 17.5 rpm, voltage phase rotation and fre-quency checks and bus tie contactor operation. The 17.5 rpm on-line test included synchronization and connection to the bus, sustained operation at below and above rated winds, transition from one fixed blade angle to the other and dynamic operation at full rated power.

3.3.3 System Checkout Test (-203) WTS #1

The general objective of this test was to verify the requirement of paragraph 3.4.4 of the System Test Plan. These requirements identified 13 test packages containing 40 items for verification by either test or demonstration (see Table 3-2).

3.3.4 System checkout Test (-204) WTS #2 and #3

System checkout for WTS #2 and #3 was based on the -203 system checkout performed on WTS #1 but greatly reduced requirements.

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Table 3-2. System Verification Requirements (Sheet 1)

SYSTEM SPECIFICATION REQUIREMENT REFERENCE		VERIFICATION METHOD*					VERIFICATION LEVEL		SECTION 4 VERIFICATION REFERENCE
PARAGRAPH NUMBER	TITLE	N/A	1	2	3	4	SUB SYSTEM	SYSTEM	
3.0	REQUIREMENTS	X							
3.1	SYSTEM DEFINITION	X							
3.1.1	General Description	X							
3.1.2	Purpose					X		x	
3.1.3	Deployment				x			x	
3.1.4	System Drawings		x					x	
3.1.5	Interface Definition	x							
3.1.5.1	Electrical Power Interface		x					X	
3.1.5.2	Communications and Control System Interface				x			x	
3.1.5.3	Utility Personnel Interface	x							
3.1.6	Customer Furnished Property	x							
3.1.6.1	Site		x					x	
3.1.6.1.1	Site Size		x						
3.1.6.1.2	Site Access Road			X					
3.1.6.1.3	Site Approvals	x							
3.1.6.2	Communications		x					x	
3.1.6.3	Power Transmission Line		x					x	
3.1.6.4	Electrical Power		x	x				x	
3.1.6.5	Color and Markings		x					x	
3.1.6.6	Mobile Data Acquisition System		x						
3.1.6.8	Utility Substation Space		x					x	
3.1.7	Operational Modes					x		x	
3.1.7.1	Automatic Modes					x			
3.1.7.2	Manual Modes					x			
3.2	CHARACTERISTICS	x							
3.2.1	System Performance and Design Requirements	x							
3.2.1.1	System Power Output			x		x		x	
3.2.1.2	Wind Speed Design Values			x				x	
3.2.1.3	Service Life			x				x	
3.2.2	Subsystem Performance and Design Requirements	x							
3.2.2.1	Control Subsystem					x		x	
3.2.2.1.1	Yaw Orientation Control					x		x	
3.2.2.1.2	Pitch Orientation Control	x							
3.2.2.1.2.1	Rotor Pitch Control					x		x	
3.2.2.1.2.2	Rotor Pitch Offset					x			
3.2.2.1.3	Teeter Brake Control					x		x	
3.2.2.1.4	Rotor Brake Control					x	x	x	
3.2.2.1.5	Rotor Parking Position Control				x			x	

*VERIFICATION METHODS: 1. Inspection 2. Analysis 3. Demonstration 4. Test

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Table 3-2. System Verification Requirements (Sheet 2)

SYSTEM SPECIFICATION REQUIREMENT REFERENCE*		VERIFICATION METHOD*					VERIFICATION LEVEL		SECTION 4 VERIFICATION REFERENCE
PARAGRAPH NUMBER	TITLE	N/A	1	2	3	4	SUB SYSTEM	SYSTEM	
3.2.2.1.6	Electrical Power Output Control					x	x	x	
3.2.2.1.7	Emergency Chutdown					x		x	
3.2.2.1.8	Operational Instrumentation		x				x	x	
3.2.2.1.9	Control Terminals		x				x		
3.2.2.1.10	Control Subsystem Maintenance REquirements			x					
3.2.2.1.11	Lighning Protection			x					
3.2.2.2	Rotor Subsystem		x	x		x	x	x	
3.2.2.2.1	Hub		x	x			x	x	
3.2.2.2.2	Blades		x	x			x	x	
3.2.2.2.3	Pitch Control Mechanism					x		x	
3.2.2.2.3.1	Pitch Change Rate					x	x		
3.2.2.2.3.2	Blade Feathering					x		x	
3.2.2.2.4	Teeter Brake					x		x	
3.2.2.2.6	Lightning Protection		x						
3.2.2.2.7	Ice Detection		x			x			
3.2.2.2.8	Crack Detection			x		x			
3.2.2.2.9	Rotor Maintenance			x	x				
3.2.2.3	Drive Subsystem		x			x	x	x	
3.2.2.3.1	Low Speed Shaft and Bearings		x	x			x	x	
3.2.2.3.2	Quill Shaft and Couplings			x		x	x	x	
3.2.2.3.3	Gearbox			x		x	x		
3.2.2.3.4	High Speed Shaft and Couplings		x	x	x			x	
3.2.2.3.5	Rotor Brake		x	x			x	x	
3.2.2.3.6	Lubrication System		x	x	x		x	x	
3.2.2.3.7	Lightning Protection			x					
3.2.2.3.8.1	Low Speed Shaft		x	x					
3.2.2.3.8.2	Gearbox		x	x					
3.2.2.4	Nacelle Subsystem		x	x		x	x	x	
3.2.2.4.1	Nacelle Structure		x	x	x		x	x	
3.2.2.4.2	Yaw Drive System		x	x		x	x	x	
3.2.2.4.3	Environmental Control Equipment		x	x			x		
3.2.2.4.4	Nacelle Personnel and Maintenance		x			x	x	x	
3.2.2.4.5	Lightning Protection			x				x	
3.2.2.5	Tower Subsystem		x				x		
3.2.2.5.1	Tower Structure		x	x			x	x	
3.2.2.5.2	Lightning Protection			x					
3.2.2.5.3	Nacelle Access Device				x	x		x	
3.2.2.5.4	Tower Electrical Outlets		x						

*VERIFICATION METHODS: 1. Inspection 2. Analysis 3. Demonstration 4. Test

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Table 3-2. System Verification Requirements (Sheet 3)

SYSTEM SPECIFICATION REQUIREMENT REFERENCE		VERIFICATION METHOD*					VERIFICATION LEVEL		SECTION 4 VERIFICATION REFERENCE
PARAGRAPH NUMBER	TITLE	N/A	1	2	3	4	SUB SYSTEM	SYSTEM	
3.2.2.5.5	Tower Interior Lighting		x						
3.2.2.6	Electrical Power Subsystem	x							
3.2.2.6.1	Functions			x				x	
3.2.2.6.2	Equipment		x			x	x		
3.2.2.6.3	Instrumentation		x			x		x	
3.2.2.6.4	Accessory Power			x		x			
3.2.2.7	Communications - Nacelle to Tower Base		x						
3.2.2.8	Engineering Instrumentation		x	x			x		
3.2.2.9	Obstruction Marking and Lighting		x						
3.2.2.10	Site Security Subsystem		x		x				
3.2.3	Reliability			x				x	
3.2.4	Maintainability	x							
3.2.4.1	Quantitative Requirements			x				x	
3.2.4.2	Qualitative Requirements	x							
3.2.4.2.1	Access		x					x	
3.2.4.2.2	Handling		x					x	
3.2.4.2.3	Test Equipment			x				x	
3.2.4.2.4	Skill Levels			x					
3.2.4.2.5	Special Maintenance Features	x							
3.2.4.2.5.1	Rotor Lock Mechanisms		x	x					
3.2.4.2.5.2	Rotor Access Device		x	x					
3.2.4.2.5.3	Rotor Teeter Position and Lock		x	x					
3.2.4.2.5.4	Major Component Removals		x						
3.2.4.2.5.5	Nacelle Monorails		x	x					
3.2.5	Availability			x				x	
3.2.6	Environmental Conditions	x							
3.2.6.1	Wind Environment			x				x	
3.2.6.1.1	Wind Gradient			x				x	
3.2.6.1.2	Wind Speed Duration			x				x	
3.2.6.1.3	Gust Design Criteria			x					
3.2.6.2	Other Environmental Conditions			x				x	
3.2.6.3	Lightning Protection Requirements			x				x	
3.2.6.3.1	Lightning Environment			x				x	
3.2.6.3.2	Lightning Design Requirements		x	x				x	
3.2.6.4	Altitude Temperature Environment			x					
3.2.6.5	Altitude Mass Density			x					

*VERIFICATION METHODS: 1. Inspection 2. Analysis 3. Demonstration 4. Test

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Table 3-2. System Verification Requirements (Sheet 4)

SYSTEM SPECIFICATION REQUIREMENT REFERENCE		VERIFICATION METHOD*					VERIFICATION LEVEL		SECTION 4 VERIFICATION REFERENCE
PARAGRAPH NUMBER	TITLE	N/A	1	2	3	4	SUB SYSTEM	SYSTEM	
3.3.6	Human Engineering				x			x	
3.3.7	Finishes		x	x					
3.4	Documentation		x						
3.5	Logistics	x							
3.5.1	Maintenance		x					x	
3.5.1.1	Spares Requirements		x					x	
3.5.2	Facilities and Facility Equipment		x					x	
3.6	Personnel and Training	x							
3.6.1	Personnel Requirements				x			x	
3.6.2	Training				x			x	
3.7	Procedence			x				x	
3.2.4.2.5.6	Rotor Tip Manual Positioning		x	x					
3.2.4.2.5.7	Gearbox Maintenance		x						
3.2.4.2.5.8	Rotor Positioning			x					
3.2.4.2.5.9	Tip Blade Removal		x	x					
3.2.4.2.5.10	Hoist System from Ground to Nacelle		x	x					
3.2.7	Transportability			x	x		x	x	
3.2.7.1	Weight and Dimensional constraints		x	x			x	x	
3.2.7.2	Qualitative Handling & Transport Requirements		x					x	
3.2.8	Installation and Checkout	x							
3.2.8.1	Site Preparation		x	x				x	
3.2.8.2	Tower Foundation			x					
3.2.8.3	On-Site Assembly		x						
3.2.8.4	Tower Erection		x				x		
3.2.8.5	Subsystem Installation		x					x	
3.2.8.6	System Checkout					x		x	
3.2.8.7	Licenses and Permits		x						
3.3	Design and Construction	x							
3.3.1	Materials, Processes and Parts		x	x		x	x		
3.3.2	Nameplates and Product Marking		x				x		
3.3.3	Workmanship		x				x	x	
3.3.4	Interchangeability		x				x		
3.3.5	Fail Safe Operation and Personnel Safety	x							
3.3.5.1	Fail Safe Operation			x	x			x	
3.3.5.2	Personnel Safety		x	x	x			x	

*VERIFICATION METHODS: 1. Inspection 2. Analysis 3. Demonstration 4. Test

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3.4 ACCEPTANCE TESTS (-300)

A series of tests were conducted on each wind turbine as required by paragraph 2.6.3 of the contract Statement of Work. The results of these tests provided the basis for customer acceptance of the completed system. Figure 3-6 shows the documentation used.

For WTS #1, the requirements for these tests originated from the System Test Plan. This required completion of 137 test conditions. For WTS #2 and #3, and rebuild of WTS #1, the requirements were consolidated into 52 test conditions. Tables 3-3 and 3-4 summarize the acceptance requirements and show the conditions completed.

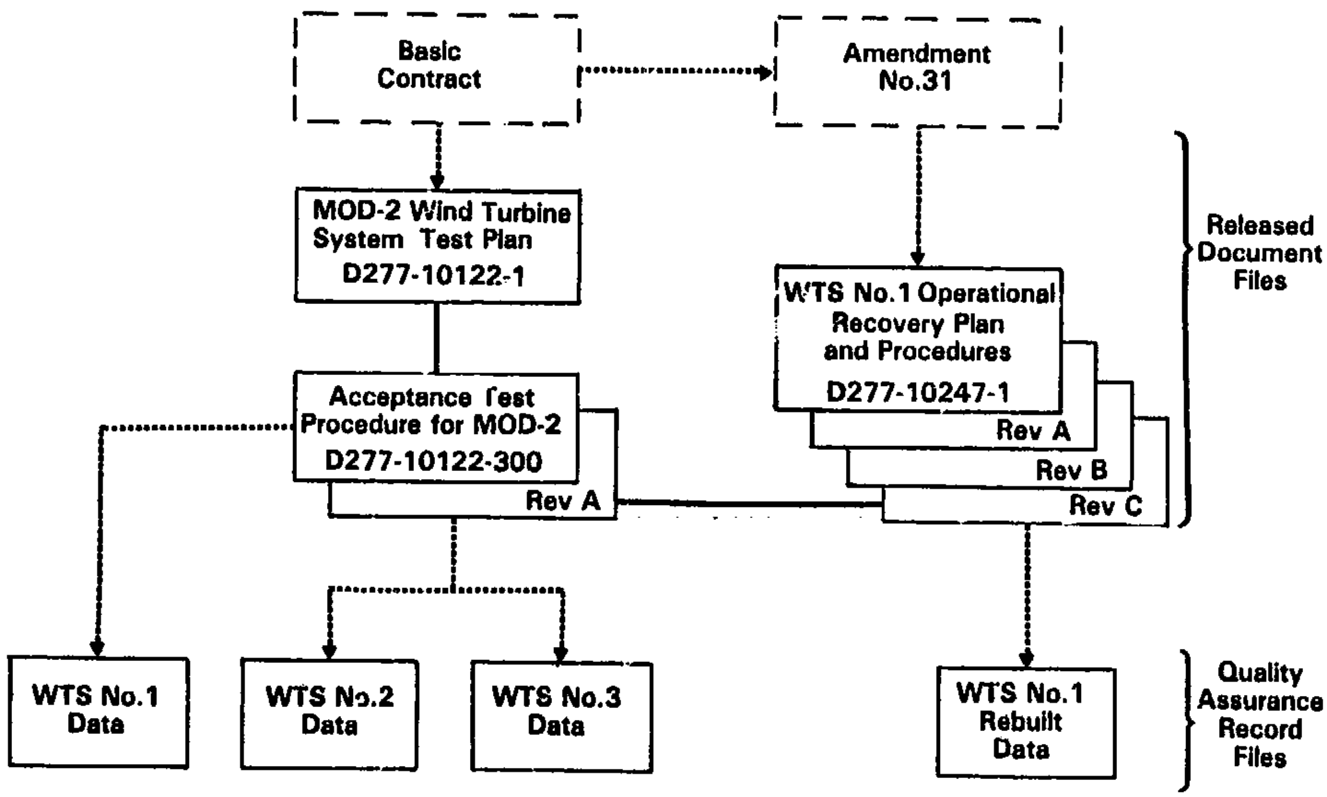

Figure 3-6. Acceptance Test Documentation

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Table 3-3. WTS No. 1 Acceptance Tests

Requirements [1]	No. of samples/conditions	
	planned	completed
Startup mode		
Low speed start up	8	8
High speed start up	3	3
Mid speed start up	5	6
Any start up	8	8
Shutdown mode		
Shutdown on decreasing wind	3	3
Shutdown on increasing wind	3	0 [2]
High speed shutdown	3	3
Low speed shutdown	3	3
Mid speed shutdown	5	5
Any shutdown	7	7
Emergency shutdowns	6	6
Standby mode (parked)		
Winds 35-45 mph	18	18
Winds>60 mph	4	0 [2]
Operate mode		
Winds 14-27 mph	12	12
Winds 27-33 mph	12	12
Winds 33-45 mph	12	12
Any wind speed	12	12
Remote operation		
24 hr test (controlled from Dittmer)	1	1
Power versus wind speed plot	1	1
100 hrs operation	1	1
Operational mode demonstration	4	4
Operations handbook demonstration	6	6
Total—	137	130

[1] Per D277-10122-1 (MOD-2 System test plan) as approved in tech directive No. 21 2/4/80

[2] Required wind conditions did not occur.

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Table 3-4. WTS Numbers 2, 3 and Rebuilt Number 1 Acceptance Tests

Requirements [1]	No. of samples/conditions planned	No. of samples/conditions completed		
		WTS No.2	WTS No.3	WTS No.1 (Rebuilt)
Start-up conditions				
Low speed (14-20 mph)	5	5	5	5
Mid speed (20-38 mph)	4	4	4	4
Hi speed (38-44 mph)	2	2	2	2
Any speed	4	4	4	4
Shut-down conditions				
Low speed (4-20 mph)	2	2	2	2
Mid speed (20-38 mph)	2	2	2	2
Hi speed (38-44 mph)	2	2	2	2
Any speed	7	7	7	7
Emergency shut-down conditions	2	2	2	2
Operate mode conditions				
14-27 mph 2 hrs (min)	2	2	2	2
27-33 mph 1 hr (min)	2	2	2	2
33-45 mph 30 minutes (min)	2	2	2	2
Any speed 10 minutes (min)	9	9	9	9
Remote operation				
8 hr test (controlled from Dittmer)	1	1	1	1
Power versus wind speed plot	1	1	1	1
100 hrs operation	1	1	1	1
Operational mode demonstration	4	4	4	4
Total samples/conditions	52	52	52	52

[1] Per D277-10122-1 (MOD-2 System test plan) as approved in tech directive No. 21, 2/4/80.

3.5 OTHER TESTS

Three specific types of tests have been or are being conducted at Goldendale since the machines have been operational. These are:

a) Acoustic Noise
b) Television Interference (TVI)
c) Wake Measurements

These tests are being conducted under the auspices of the Test Project Review Board with participation from BEC, BPA, Pacific Northwest Laboratory (PNL), Solar Energy Research Institute (SERI), University of Michigan, and Oregon State University.

3.5.1 Acoustic Noise

In the spring of 1982 SERI conducted a series of tests over a period of six weeks to measure the acoustic noise emission and effects during single and multiple wind turbine operations. The tests included the use of noise measuring instrumentation on the ground, on the wind turbine tower and airborne, using a balloon. DOE/NASA Document TM 20305-8 (March 1982) provides planning details. Data collected was incomplete due to factors such as suitable wind conditions, wind turbine operations, and instrumentation difficulties. Data are currently being reduced and analyzed by SERI.

NASA Langley made recordings of the acoustic noise from single and multiple turbine machine operation in May 1982 and is currently processing and analyzing the data.

3.5.2 TVI

SERI, University of Michigan and BPA collaborated in measurements of TVI from the MOD-2 wind turbine system. DOE/NASA Document TM 20305-8 (March 1982) provides planning details. Static data (machine not rotating) were taken using TV stations at Pasco and Portland as the sources. Dynamic data (machine rotating) were incomplete due to lack of data with WTS #1 operating alone. Data are currently being analyzed by the University of Michigan.

3.5.3 Wake Tests

In the summer of 1982 PNL conducted a series of tests to:

a) Document qualitative and limited quantitative information gathered through flow visualization techniques that define the MOD-2 wake geometry, wake swirl and rotor tip vortex persistence.

b) Determine the centerline velocity deficit and its variation with downwind distance.

Reference 3 provides planning details. Techniques included smoke generator and balloon supported instrumentation. Results of these tests will be presented by PNL.

Oregon State University conducted wind flow evaluations near WTS #1 using kites flown at various altitudes. The objective was to define the structure of the wake surrounding WTS #1 and to compare these results with a modified version of the AeroVironment wake model. Data is currently being evaluated by OSU.

4.0 CONTROL SYSTEM DEVELOPMENT

4.1 SUMMARY

Since the MOD-2 wind turbine system operation began, a continuing effort has been made to improve the control system performance. The baseline system (February 1981) was reasonably successful in satisfying the original design goals. However, due to excessive cyclic structural loads, modifications to the pitch control algorithm were warranted.

After extensive testing, analysis, and redesign, the pitch control configuration arrived at operates satisfactorily and meets the three design objectives; namely, good system stability, good power quality, and decreased cyclic structural loads; however, the annual energy output of the machines has decreased. An improved control algorithm is presently being tested which will meet all design objectives and increase annual energy production.

4.2 BASELINE SYSTEM DESCRIPTION

The MOD-2 control system provides the sensing, computation, and commands necessary for unattended operation of the WTS. The pitch control system is that portion of the control system which regulates the angle of attack of the outboard section of the rotor (rotor tips). Adjusting the tip angle of attack is the method used to control power levels and quality, as well as alleviating structural loads.

4.2.1 Design Objectives

The baseline pitch control system was designed to operate in the wind regime outlined in the MOD-2 System Specification. Specific requirements in that document that apply to the Pitch Control System either directly or indirectly are discussed in the following section.

4.2.1.1 Steady Wind Speed

The two regions of power production defined for the baseline MOD-2 WTS were above and below "rated" wind speed (V_r = 28 mph). The region from V_r to the high wind speed cutout (V_{CO} = 45mph) was the above rated wind speed operating regime. The design objective in this regime was to produce the rated power output (2.5 MW) with small variations due to gusts.

For wind speeds below V_r, the design objective was to maximize the power output by staying as close as possible to maximum coefficient of power (CP) operating conditions.

4.2.1.2 Wind Gusts

A "design gust" (Vw > 28%, 13.8 sec. duration) was determined by statistical operations, after truncation of the power spectral density curve of expected gusts across the 300 ft diameter rotor, for gusts below 30 seconds in duration. This gust profile has a 1-COS shape. A "loads gust" (Vw > 41%, 30 sec. duration) was also defined.

The baseline design objectives relating to wind gusts were:

1) Maintain drive train torque transients due to the design gust to less than 5% above rated torque.

2) Maintain drive train torque transients due to the loads gust to be less than 58% above rated torque.

4.2.1.3 Twice Per Revolution (2P) Alternating Torques

Wind shear and nacelle yaw angle with respect to the wind, contribute to drive train disturbance torques at 2P. Since both the above rated and below rated algorithms will respond to this 2P disturbance and actuator motion at 2P is undesirable another baseline design goal was to minimize this motion.

4.2.2 Baseline Configuration

A preliminary design which supported the above objectives was defined and analyzed. This design was then implemented with a microprocessor based onboard system. The control system is illustrated by the Figure 4-1 block diagram. The initial baseline control algorithms were characterized by the following:

1) Below rated operation had two pitch set points; 3 degrees and 5 degrees. In addition, hub-rate error was fed back to increase system damping.

Note: The initial control system design utilized pitch set points of -1 degree and +3 degrees without hub rate damping. The addition of hub rate damping early in the field test program necessitated changing to the +3 and +5 degree set points.

2) Above rated operation utilized proportional plus integral control of power output in addition to the hub rate error feedback.

3) There was no hysteresis included in the transition region (between below and above rated operation).

4) A 2P notch filter was used in the control pitch command output.

4.2.3 Baseline Test Results

The baseline control system described above was in place in February 1981. During March and April stable operation was observed. The winds during that time period were relatively light and steady. When the above rated mode was reached, the power quality was quite good (± 350 kW). Also, drive train torque transients were acceptable. The design objectives, as out-lined above, seemed to have been met. However, when operations resumed in the fall of 1981, much more turbulence in the wind showed a stability problem at and above rated wind and the cyclic structural loads were found to be considerably higher than the anticipated levels. These high load levels have an adverse impact on system life and repair frequency.

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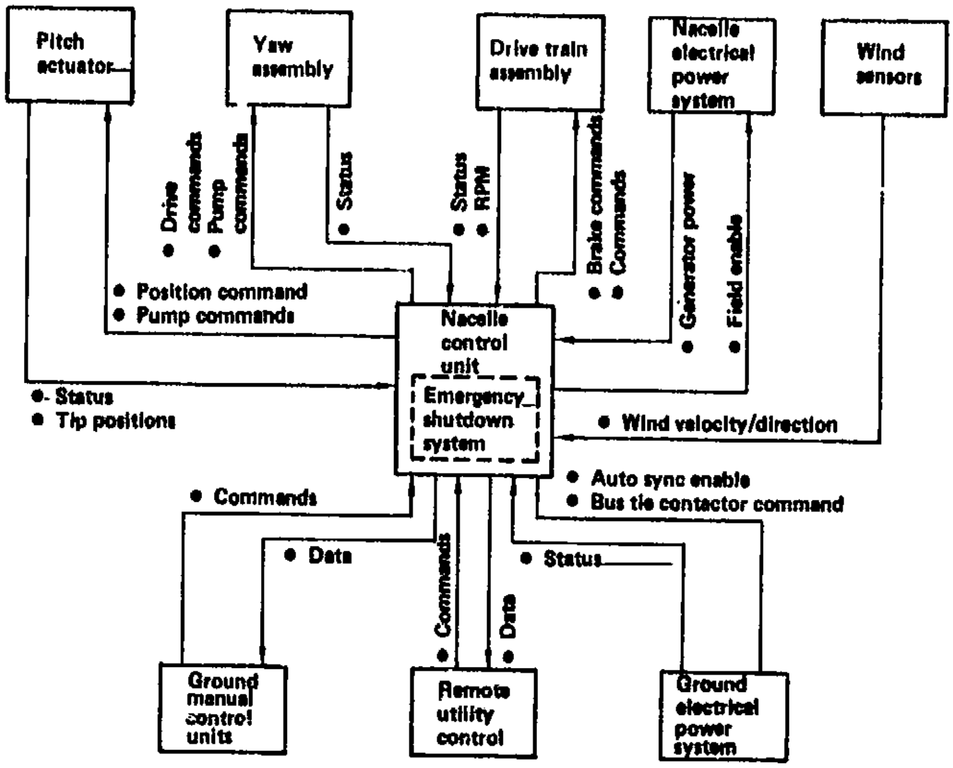

Figure 4-1. Control System Block Diagram

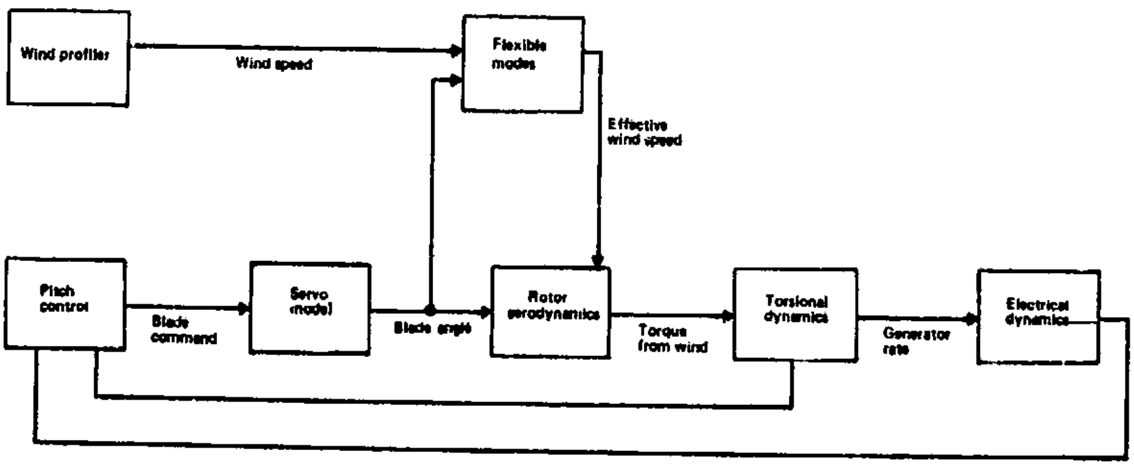

Figure 4-2. Simulation Block Diagram

4.3 SYSTEM IMPROVEMENTS

Since February 1981, an ongoing analysis effort has been made to modify and improve the baseline pitch control system design with the objective of improving stability and reducing cyclic structural loads.

A plan was drafted to perform the analyses required to reach the above objective. Three major analysis tasks were performed. First, the dynamic simulation model of the MOD-2 was improved in order to increase the validity of predictions. Second, modifications of the pitch control algorithm designed to increase stability were evaluated with the improved simulation. And third, various notch filter designs were evaluated in an attempt to reduce cyclic structural loads.

4.3.1 Dynamic Model Improvements

The dynamic control system analysis of the MOD-2 is performed with a non-linear model written in the EASY5 simulation language. A block diagram of this simulation model is shown in Figure 4-2, and its features are summarized in Figure 4-3. During the control improvements study, the following enhancements were made to this model.

1) A model of the two dominant flexible modes of the tower/rotor structure was incorporated. In this model, bending moments are calculated which can be directly related to the moments measured in the field.

2) Digitized, real wind time history data were incorporated as the forcing function.

3) The capability to calculate power spectral densities of simulated loads was added.

4.3.2 Stability Modifications

Two modifications to the pitch control algorithm, designed to increase stability, were tested in the simulation; hysteresis was added at the control mode transition and the control gains were optimized. These modifications proved very promising and were later tested in the field and incorporated.

4.3.3 Notch Filter Design

Since most of the cyclic structural loads occurred at two distinct frequencies (the tower natural frequency - .36 Hz, and the rotor natural frequency - 1 hz) it was decided to investigate the use of notch filters in order to reduce any coupling between the structure and control system at these frequencies. Many notch filters were investigated with the simulation. Of these, only a few were actually tested in the field.

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EASY MODEL SIMULATION CAPABILITY

FEATURES

- ACTUAL WIND INPUTS--
- AERODYNAMIC DRIVETRAIN STRUCTURAL COUPLING
- MODELS CONTROLS ALGORITHMS
- NONLINEAR SERVO MODEL
- NONLINEAR AERODYNAMICS BASED ON RELATIVE WIND
- PSD
- TIME HISTORY
- STATISTICAL LOADS ANALYSIS
- STABILITY ANALYSIS

LIMITATIONS

- DOES NOT SIMULATE 1P OR 2P
- ASSUMES INPUT WIND UNIFORM OVER DISK
- DOES NOT SIMULATE TEETER

Figure 4-3. Simulation Capability

Table 4-1. Control System Improvements

	Feb '81 Baseline	June thru Dec '81	Jan '82	Feb '82	April '82	July '82
Configuration	2P Notch filter	−9 db Tower notch filter	Control loop gain changes hysteresis added	−23 bd Tower notch filter revised gains	−15 db Blade notch filter	−23 db Tower notch filter, revised gains, 5° below rated pitch schedule, 0° pitch limit
Stability	Limited stability	Marginal stability	Improved stability above/below rated transition problems	Improved stability above/below rated transition problems	Improved stability above/below rated transition problems	Stable
Power quality	±350 kW	±750 kW	±200 kW	±250 kW	±250 kW	±250 kW
Tower cyclic loads	100%	64%	64%	27%	27%	27%
Rotor cyclic loads	100%	100%	100%	100%	Negligible improvement	100%

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4.3.4 Analysis Results

Table 4-1 summarizes the performance predictions made with the simulation as the pitch system configuration evolved from February 1981 to July 1982. As shown, the analysis indicated that each design change improved the MOD-2 performance. The July 1982 configuration is currently in use.

4.4 FINAL SYSTEM DESCRIPTION

The control system was operating satisfactorily in February and April 1982 and meeting the three objectives established above in the rated mode; namely, increased stability, good power quality, and decreased cyclic structural loads. However, the above improvements were followed by an instability occurring at the above/below rated transition region. This condition is aggravated by the blade pitch being driven beyond the maximum C_p and causing negative damping (oscillation, excitation) instead of damping. To minimize this condition, a pitch command limit of 0° and a 5° below rated nominal pitch setting has been implemented as an interim measure. Limited operation at this time in both above and below rated modes has not observed a stability problem. The pitch control algorithms currently in use are shown in Figure 4-5.

An effort is underway to achieve more below rated power by operating closer to the maximum C_p below rated, delete the mode change steps and maintain stability margins. Initial tests results of the improved algorithm show a significant improvement. This effort is scheduled for completion at the end of October.

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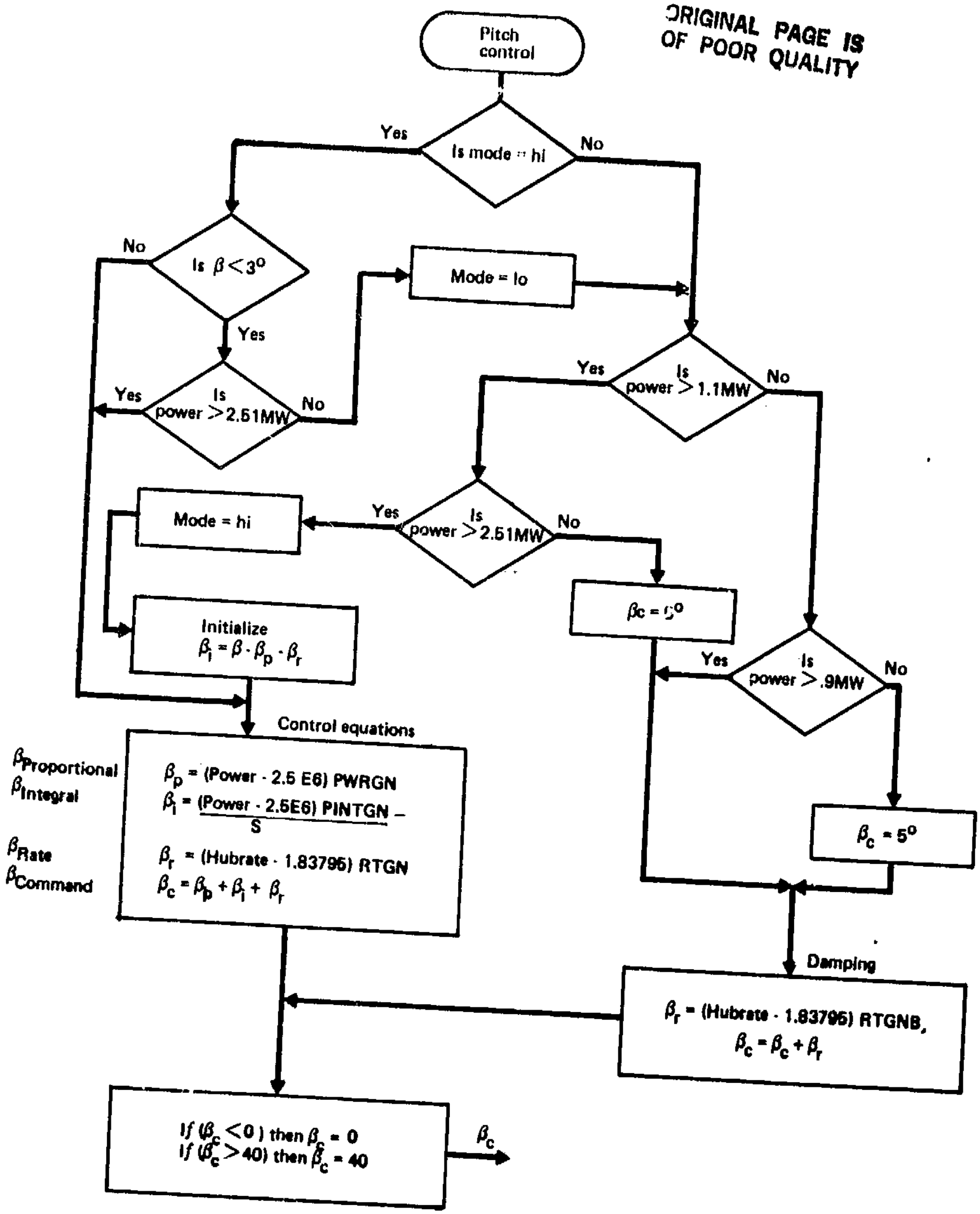

Figure 4-4. Pitch Control Algorithm

5.0 INITIAL OPERATION

This section discusses the performance of the MOD-2 WTS during its initial operating period. Information presented on system performance and loads is based on data gathered from January 1981 through mid May 1982. Availability and maintenance experience data covers the period January 1981 through early June 1982.

5.1 AERODYNAMIC PERFORMANCE

5.1.1 Power Variation with Wind Speed

The power variation with wind speed for the three MOD-2 units at Goldendale, is shown in Figures 5-1 through 5-3. The first and second figures refer to units #3 and #2, respectively. The third figure is for unit #1. In all three figures, the power was measured at the generator output terminals and the wind speed was measured at the 195 ft. level of the BPA meterological tower.

The data shown in the first two figures were generated by computer analysis of data recorded on magnetic tape at the site. Each data point represents an average value for a ten minute interval. The time intervals were identified by searching the real time brush recorder charts from the site. For operation below rated power, the pitch angle throughout the entire time interval was either +3 or +5 degrees. To minimize data scatter, intervals were selected where the wind was reasonably smooth. The total variation in power during any time interval was usually less than 500 kW. The time scale for these power variations was several minutes. Almost all of the below rated power data points occurred during the night hours. For operations at rated power, the only criterion used to identify time intervals was that the entire interval be rated power operation. After the time intervals were identified, the wind speed and generator power channels were digitized at a sampling rate of 10 per second. Average values were then computed.

The data shown in Figure 5-3 were obtained by manually averaging brush recorder traces over time intervals of several minutes. The time intervals were selected so that power and wind speed signals were relatively smooth.

The data shown in the three figures correlate quite well with the predictions from the GEM computer program used for performance predictions. In addition, there do not appear to be any significant differences between the power output measurement for the three units at Goldendale.

5.1.2 Drive Train Losses

The drive train losses for the MOD-2 wind turbine were measured by comparing the mechanical power transmitted through the quill shaft with the electrical power delivered at the generator terminals. The results are presented in Figure 5-4. Data points are presented for units #2 and #3. The averaging interval for these data points was one minute.

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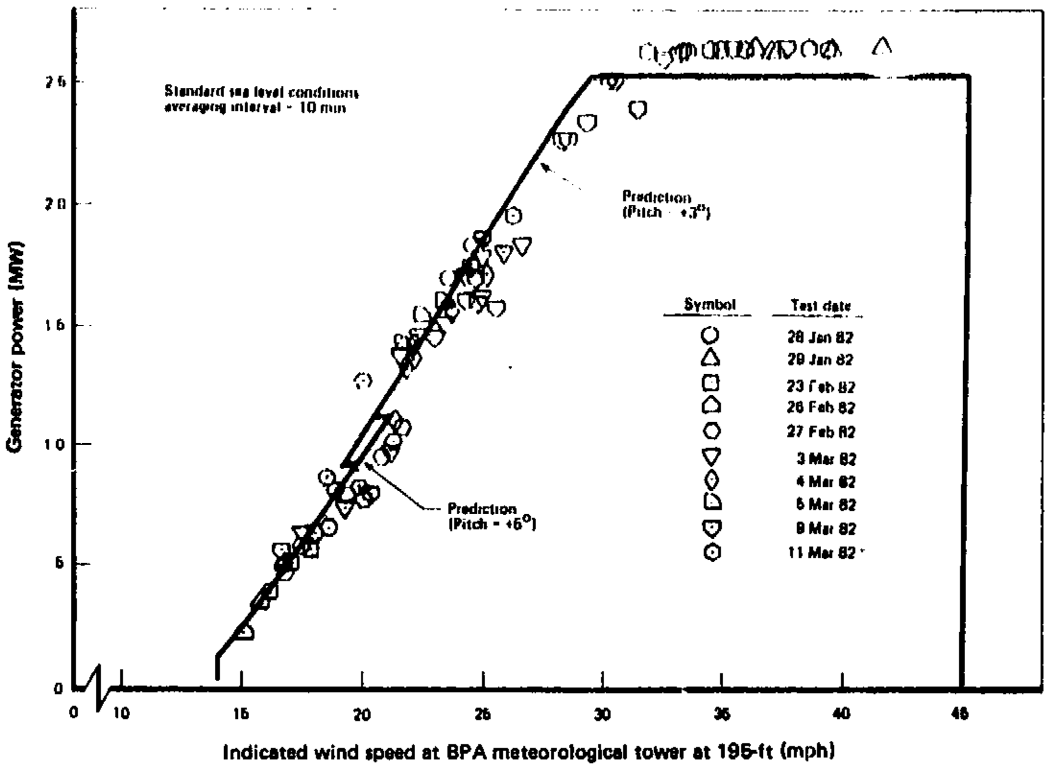

Figure 5-1. Performance Curve For Mod-2 (WTS Number 3)

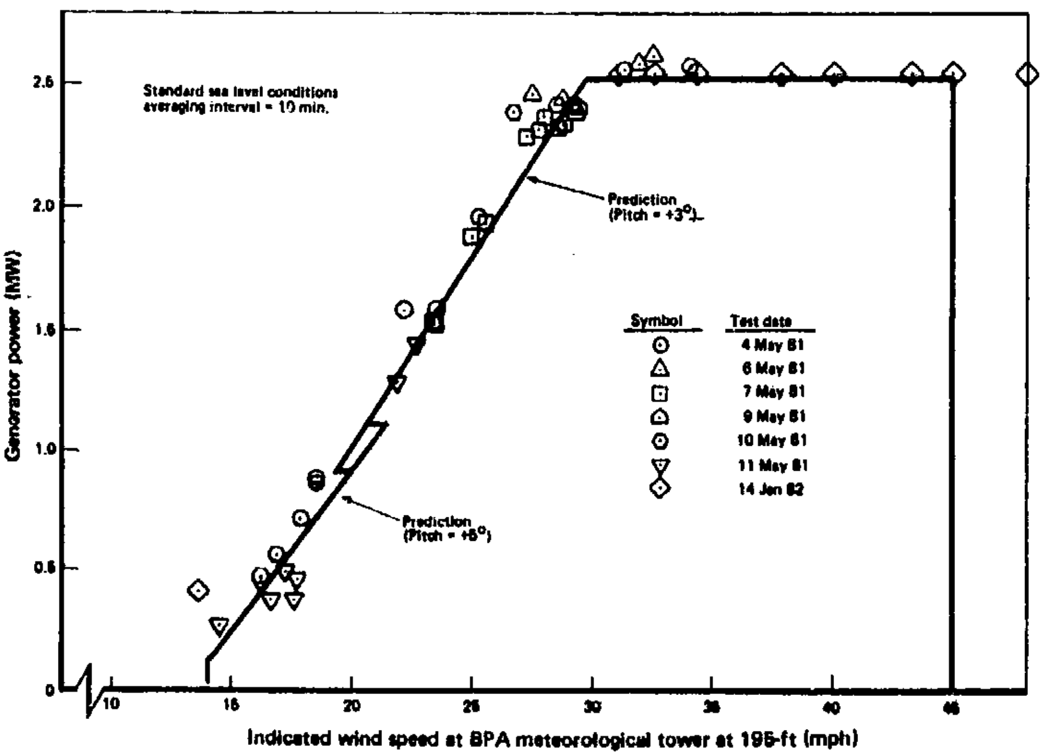

Figure 5-2. Performance Curve for Mod-2 (WTS Number 2)

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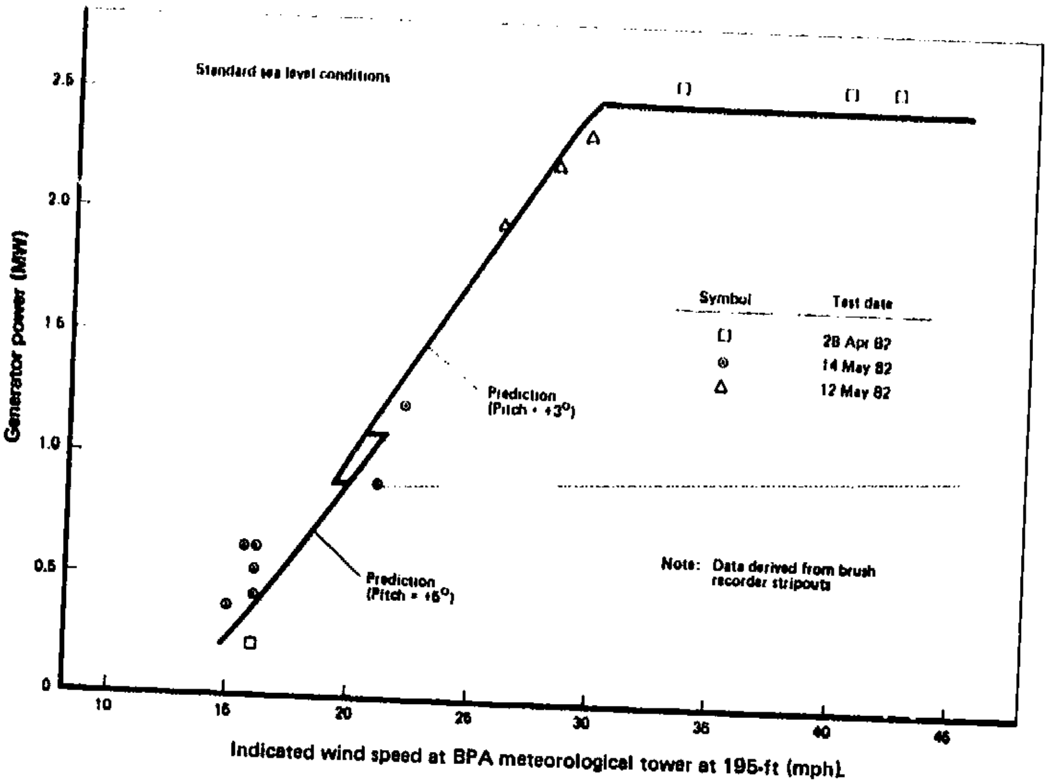

Figure 5-3 Performance Curve for Mod-2 (WTS Number 1)

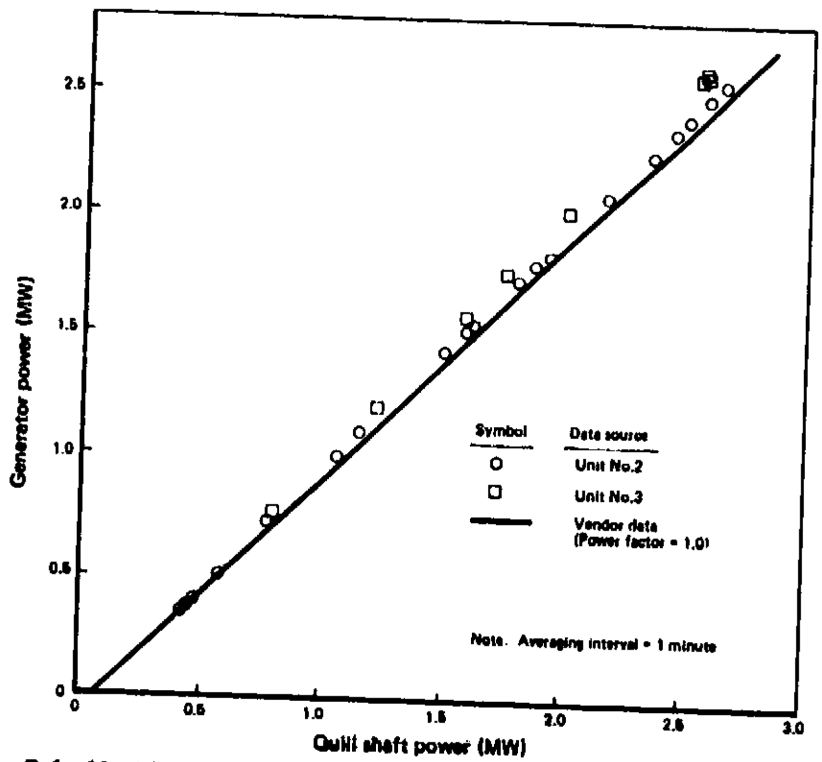

Figure 5-4. Mod-2 Electrical/Mechanical Losses Between Rotor and Generator

In Figure 5-4, the data points are compared to a vendor loss curve. The loss curve was derived by combining losses measured by the respective vendors of the gearbox and generator. Unity power factor was assumed for the generator losses.

Inspection of Figure 5-4 shows that the drive train losses measured at Goldendale are optimistic relative to the vendor data, especially at the higher power levels. The data also indicate that the unit #3 drive train is more efficient that the unit #2 drive train. The difference between the drive train losses for units #2 and #3 is larger than expected. Most of this discrepancy is attributed to the inability to obtain an accurate calibration for the quill shaft torque measuring channel.

5.1.3 Startup Time

The impact of wind speed on the time required to accelerate the rotor from zero rpm to synchronous speed was measured at Goldendale. The results are shown in Figure 5-5 for units #2 and #3.

The data show considerable scatter because of the inability to accurately measure the average wind speed during the startup. Like the predictions shown, the data indicate that the start up time is inversely proportional to wind speed. Most of the measured startup times are less than the predictions. Approximately 5 minutes are required to startup in a 20 mph wind at hub height.

5.2 STRUCTURAL ANALYSIS CORRELATION

A primary goal of the MOD-2 acceptance test program was to gather sufficient data to demonstrate that the MOD-2 WTS is operating within design load limits. The purpose of this section is to correlate the Goldendale measured loads with the MOD-2 structural design loads. The data/analysis correlation focused on the critical structural subsystems including rotor blades, pitch actuator, quill shaft and tower. Measured teeter motions and drive train and nacelle vibration environments were also correlated with MOD-2 design criteria. Based on the measured loads data, a fatigue life assessment of the MOD-2 WTS was performed for both the Goldendale and design Weibull distribution of winds.

5.2.1 Test Data Loads Analysis

The purpose of this section is to show the correlation of the MOD-2 design loads with loads measured on the Goldendale MOD-2 units during the acceptance test program. To facilitate this correlation, the operating loads data recorded on magnetic tape on site were digitized, processed, sorted into wind speed bins and analyzed statistically. The wind speed measured at the 195 foot level of the BPA met tower was used as the wind speed reference in a similar manner to the performance correlation of Section 5.1. Time histories of startup and shutdown loads were also cross plotted for correlation with design loads.

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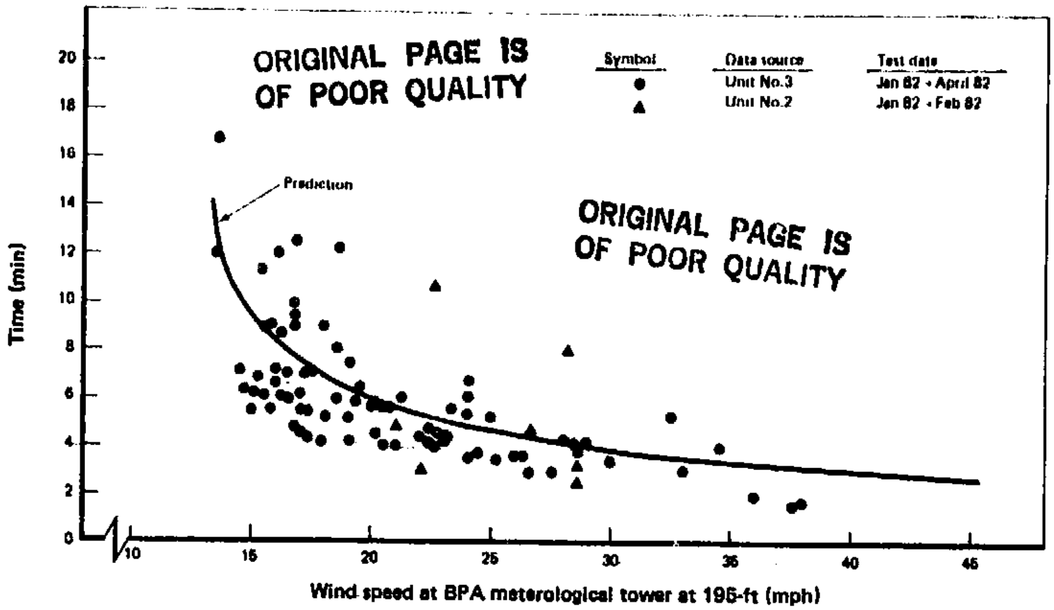

Figure 5-5. Time From Breakaway to Synch, Enable

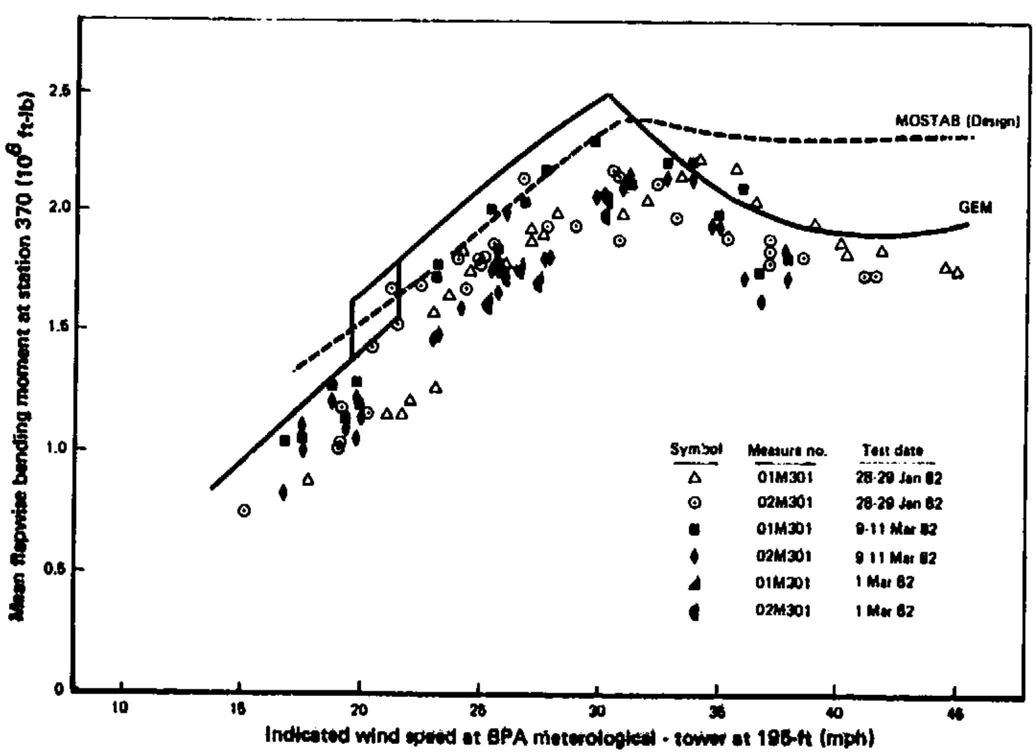

Figure 5-6. Mean Flapwise Bending Moment at Sta. 370 (WTS Number 3)

Teeter motion data was analyzed statistically for both operating and startup/shutdown conditions for correlation with design limits. The frequency content of drive train and nacelle vibrations was measured and compared to structural vibration criteria, vendor specifications and industry vibration standards.

5.2.1.1 Rotor Loads

5.2.1.1.1 Flapwise Blade Loads

Flapwise blade bending moments were measured at Sta. 370 (r/R = 0.20) and Sta. 1164 (r/R = 0.65) on both blades on each unit. Operating flapwise loads were separated into mean and cyclic components and sorted into wind speed bins over the operating envelope.

The measured mean flapwise moments at Sta. 370 are compared to design loads in Figures 5-6 to 5-8. The design loads were based on the MOSTAB computer program developed by NASA. The load predictions from the GEM program are shown for reference. Both programs appear to provide a fair representation of the loads profile actually measured. Above rated winds, the MOSTAB program conservatively envelopes the data whereas the GEM program provides a better description of blade unloading as the blade spills power. There is evidence of some machine-to-machine differences. Unit #3 does not appear to reach the load levels reached by the other two units at the same wind speed. This difference, which may be due to pitch tolerance buildup in the as-built rotor, inaccurate indication of collective pitch at the CRT, or channel calibration error, is under investigation. Overall, the correlation of measured flapwise loads with design loads is considered satisfactory.

The measured mean flapwise moments at Sta. 1164 are compared to loads predictions in Figures 5-9 and 5-10 for units #3 and #2. A cursory review of unit #1 data showed a similar profile. Both the MOSTAB and GEM programs provide a fair representation of measured data although MOSTAB appears to be slightly less than measured values below rated winds. GEM appears to provide a better representation overall.

The spanwise distribution of mean flapwise bending moment is shown in Figure 5-11. This is a cross plot of data points near rated wind (29-31 mph) for which only the mean and standard deviations ($\pm 1\sigma$) are indicated. Both MOSTAB and GEM programs provide a good representation of measured data, with GEM predictions being somewhat conservative.

The measured cyclic flapwise moments for units #3 and #2 are shown in Figures 5-12 to 5-15. Processed data for unit 2 was sparse but appears to exhibit the same trends as unit 3. Data points for both the 50 percentile and 99.9 percentile levels are shown. Nonlinear least-squares error curve fits to the cyclic loads data were developed to facilitate fatigue life calculations.

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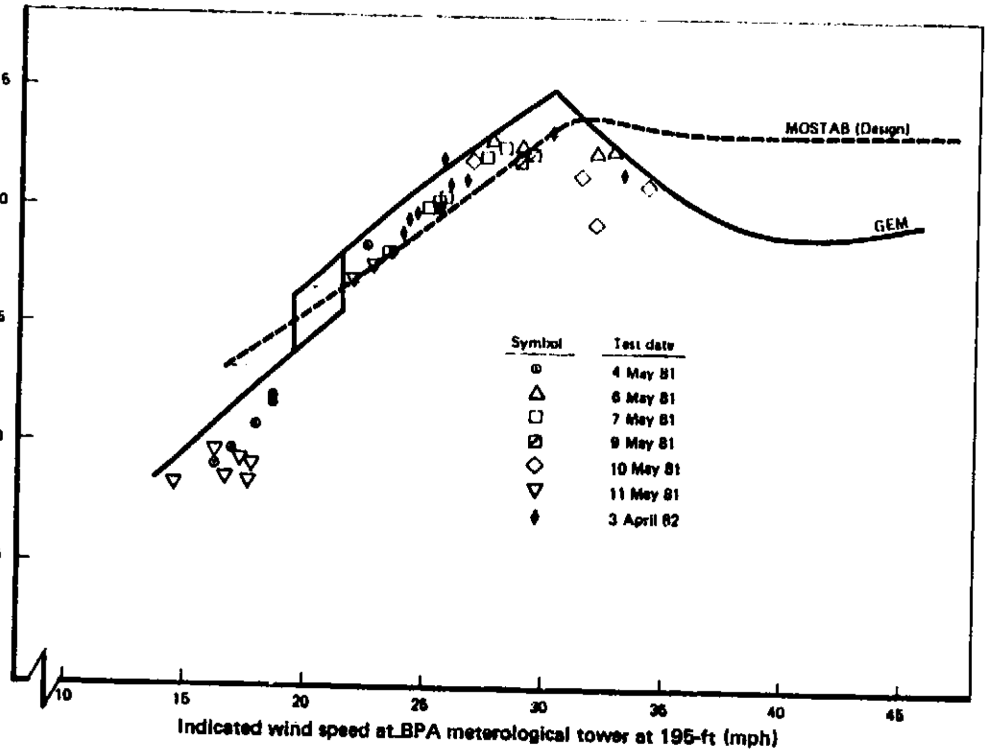

Figure 5-7. Mean Flapwise Bending Moment at Sta. 370 (WTS Number 2)

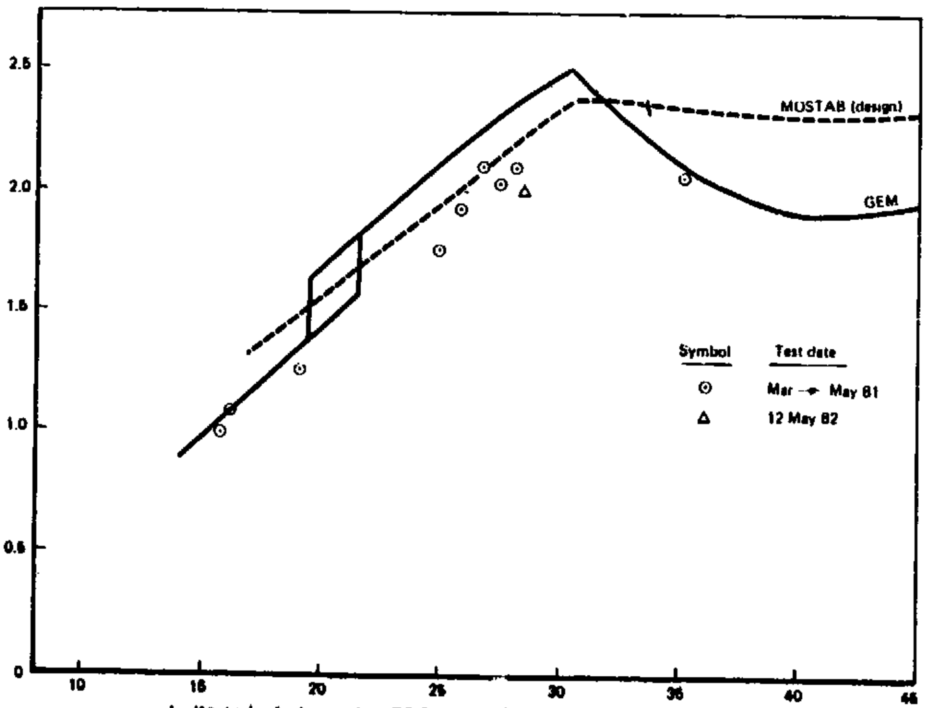

Figure 5-8. Mean Flapwise Bending Moment at Sta. 370 (WTS Number 1)

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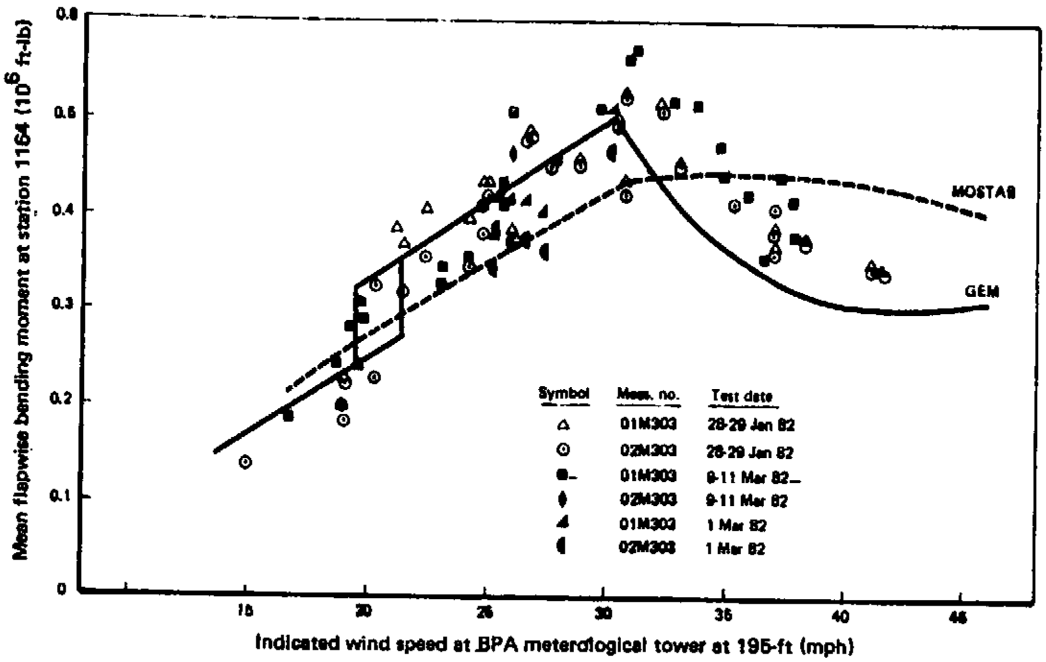

Figure 5-9. Mean Flapwise Bending Moment at Sta. 1164 (WTS Number 3)

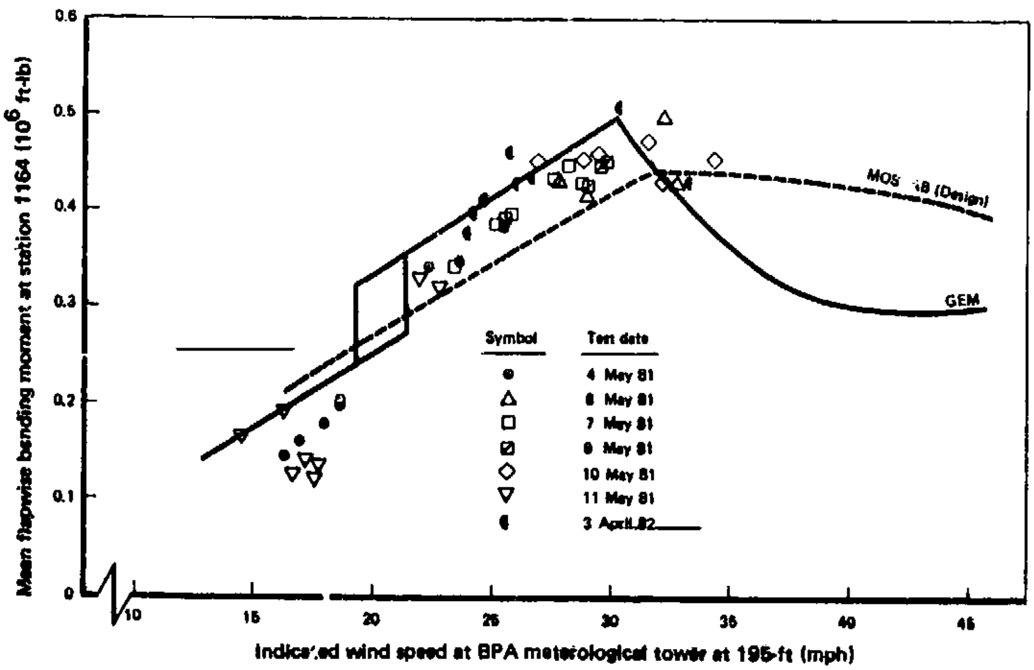

Figure 5-10. Mean Flapwise Bending Moment at Sta. 1164 (WTS Number 2)

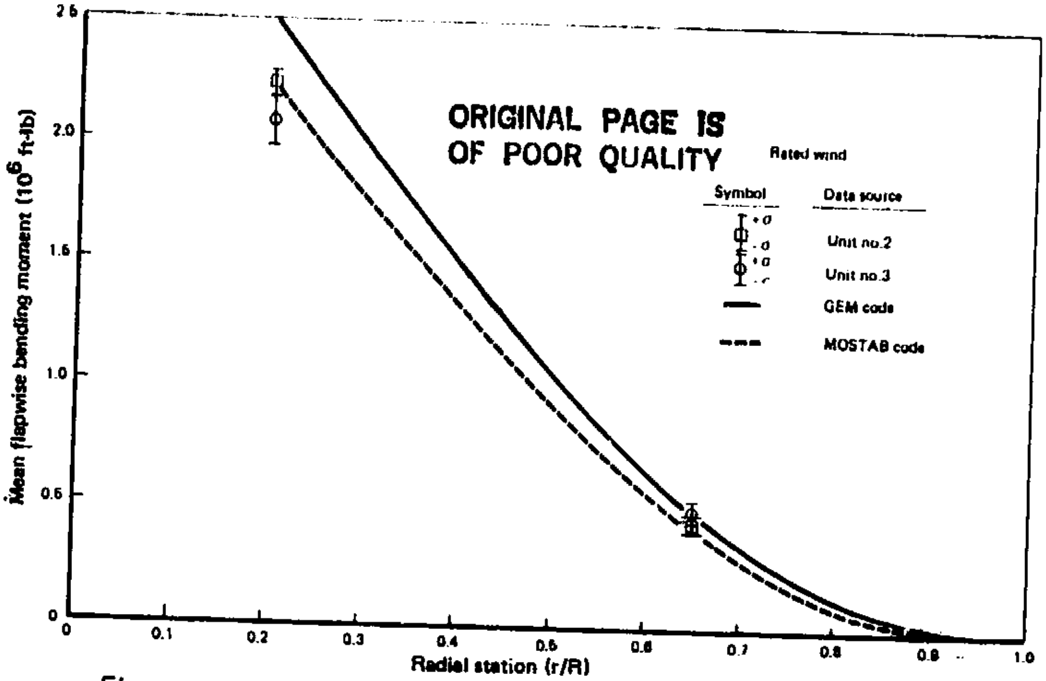

Figure 5-11. Spanwise Distribution of Mean Flapwise Bending Moment

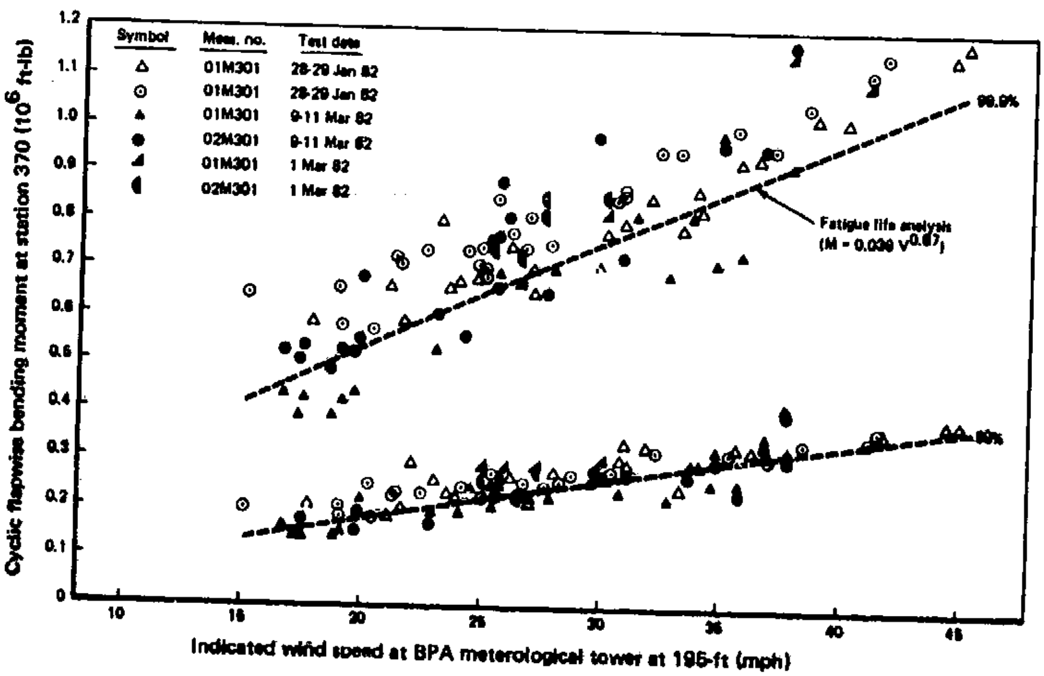

Figure 5-12. Cyclic Flapwise Bending Moment at Station 370 WTS Number 3)

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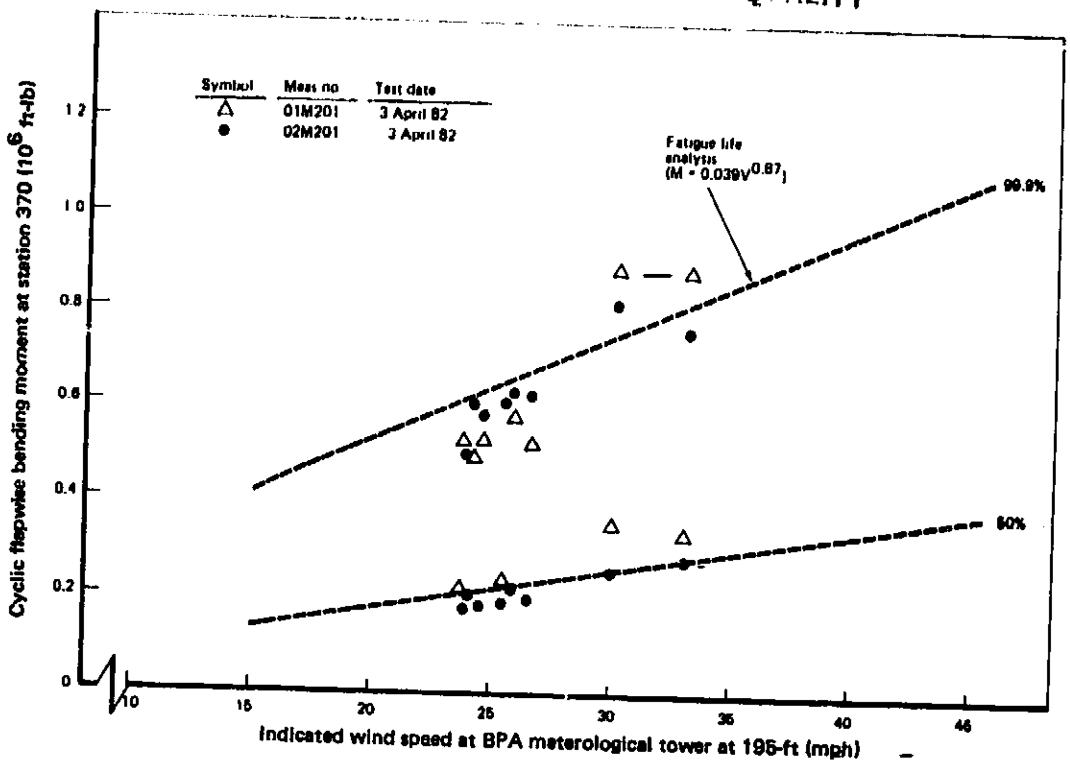

Figure 5-13. Cyclic Flapwise Bending Moment at Station 370 (WTS Number 3)

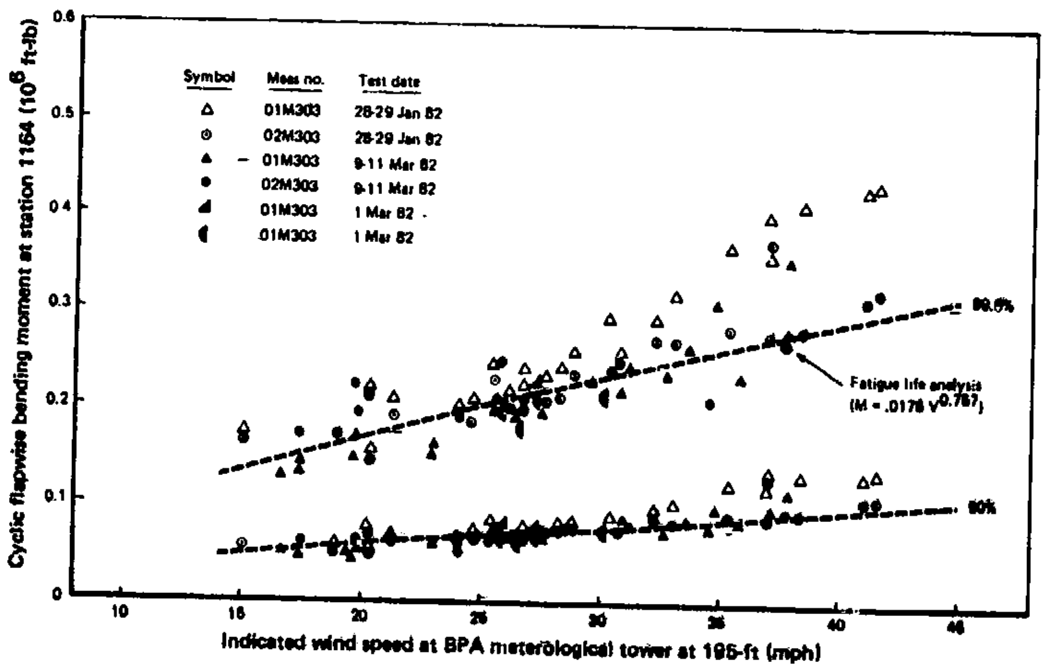

Figure 5-14. Cyclic Flapwise Bending Moment at Station 1164 (WTS Number 3)

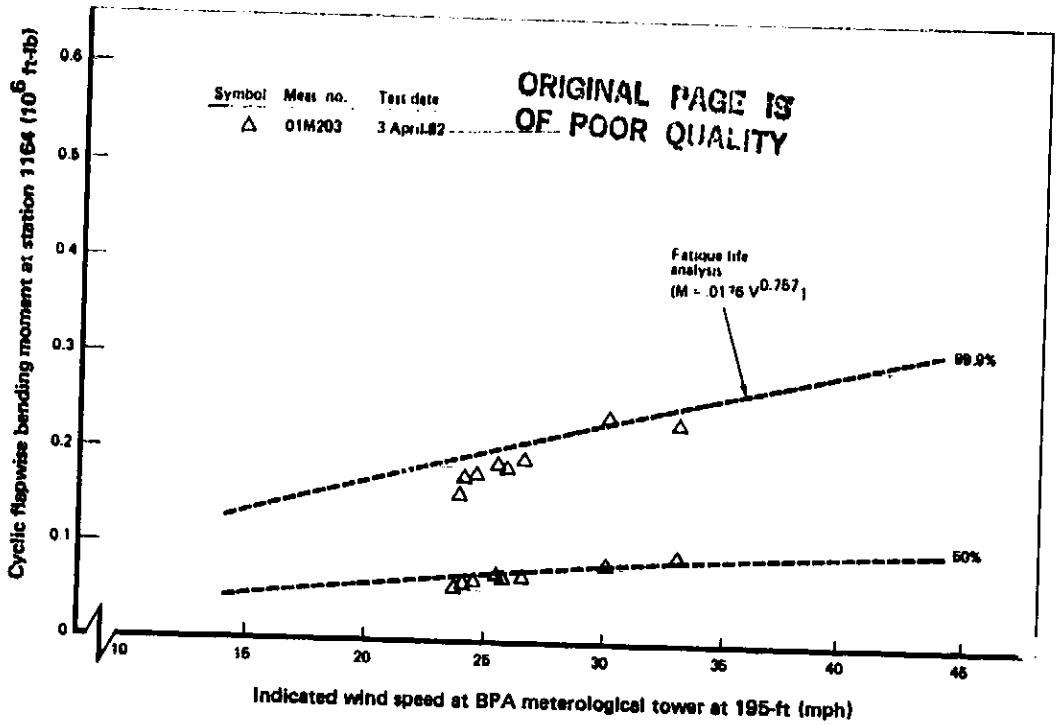

Figure 5-15. Cyclic Flapwise Bending Moment at Station 1164 (WTS Number 2)

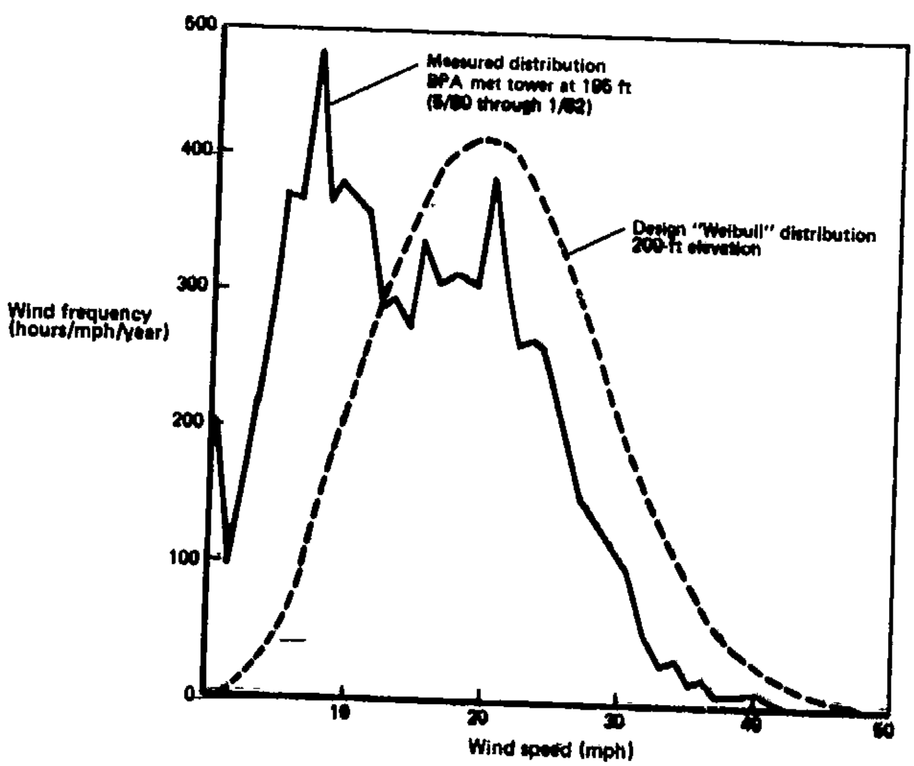

Figure 5-16. Mod-2 Wind Speed Frequency Distribution

Cyclic loads predictions in the form of the wind bins plots shown in Figures 5-12 to 5-15 were not available because of a different methodology used for cyclic loads predictions. The correlation of cyclic loads predictions and loads data, however, was possible on the total cumulative probability distributions over the 30 year life of the machine. In order to transform the cyclic loads data in wind bins form to a cumulative probability distribution, one must consider the annual distribution of mean winds. In effect, the frequency distribution of mean winds is used to weight the wind bins statistics to arrive at a total cumulative probability distribution.

The design mean wind (Weibull) distribution is compared to the measured Goldendale distribution in Figure 5-16. The latter was measured over approximately an 18 month interval. It is obvious that the design (Weibull) distribution is more severe in that more time is spent at the higher wind speeds. Since the design cyclic loads were based on an assumed Weibull distribution, this distribution was used for determining the cumulative probability distribution.

The cumulative distribution of cyclic flapwise moments is compared to the MOD-2 design loads distribution in Figures 5-17 and 5-18. At both blade stations, the test data based on the Weibull distribution exceeds the MOD-2 design loads distribution. At Sta. 370 the measured cyclic load (0.999) is 53 percent greater than design; at Sta. 1164 the measured data exceeds design by 125 percent. The cyclic loads methodology is believed to have underestimated both the narrowband turbulent response of the blade flap mode and the control system induced blade loads. The effects on fatigue life are discussed in Section 5.2.2.

5.2.1.1.2 Chordwise Blade Loads

Cyclic chordwise moments were measured at Sta. 100, 370, and 1164. The correlation of measured cyclic chordwise bending moments with MOSTAB design loads, corrected for as measured rotor weight, is shown in Figure 5-19. The data is in good agreement with prediction. Data traces indicate that the cyclic chordwise moments are primarily gravity induced (1P) with little evidence of higher frequency content. The chordwise blade mode does not couple with other structural modes.

5.2.1.1.3 Blade Startup/Shutdown Loads

Shutdown of the MOD-2 units is accomplished by feathering the blade tips at prescribed rates. The emergency shutdown feather rate is highest at initiation of shutdown and gradually decreases, averaging 5° per second; the normal shutdown rate is 1° per second. Feathering causes reversal of the flapwise bending, generally peaking when the blade pitch passes through 25° to 35°. The upwind blade surface normally in tension during operation is subjected to a compressive loading. The maximum shutdown loads occur during shutdown in near rated winds. Emergency shutdown loads are somewhat more severe than normal shutdown loads.

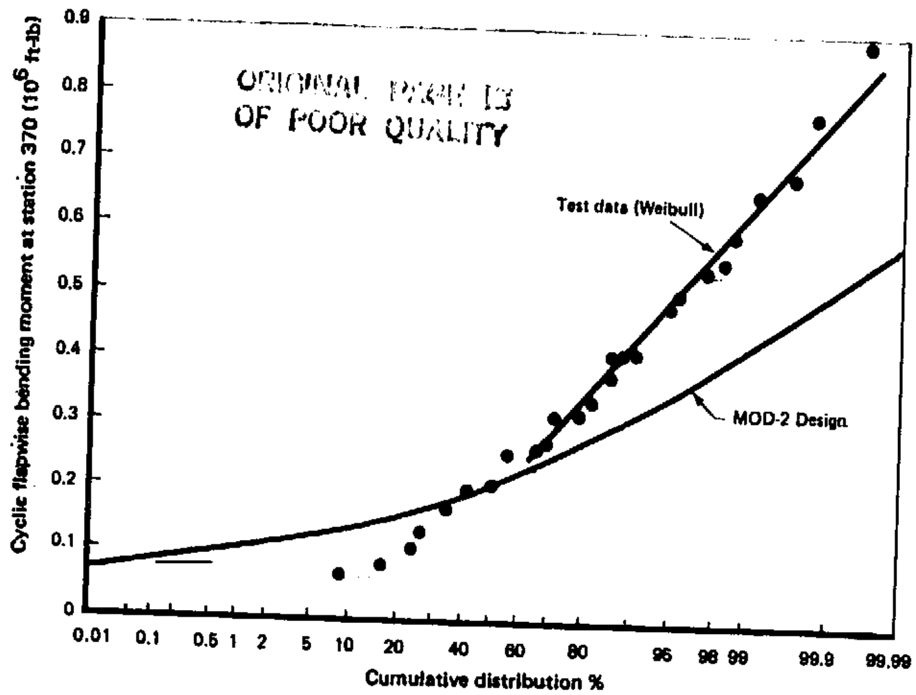

Figure 5-17. Cumulative Probability of Cyclic Flapwise Moments at Sta. 370

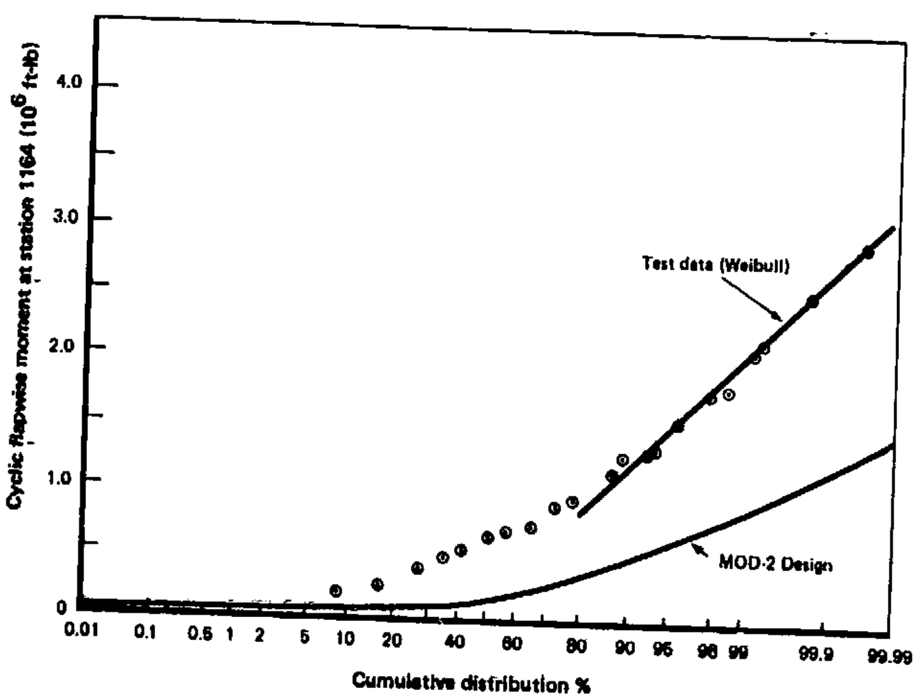

Figure 5-18. Cumulative Probability of Cyclic Flapwise Moments at Station 1164

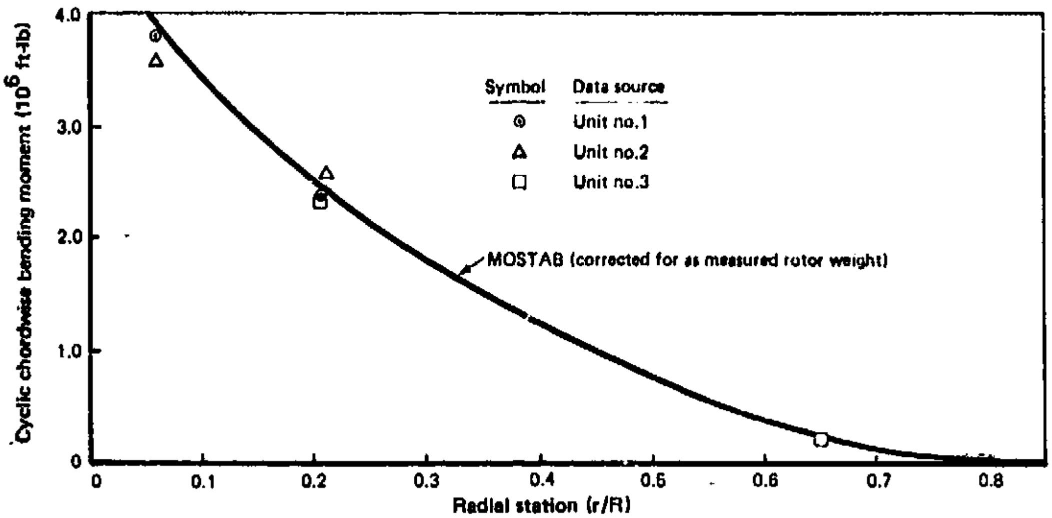

Figure 5-19. Spanwise Distribution of Cyclic Chordwise Bending Moment

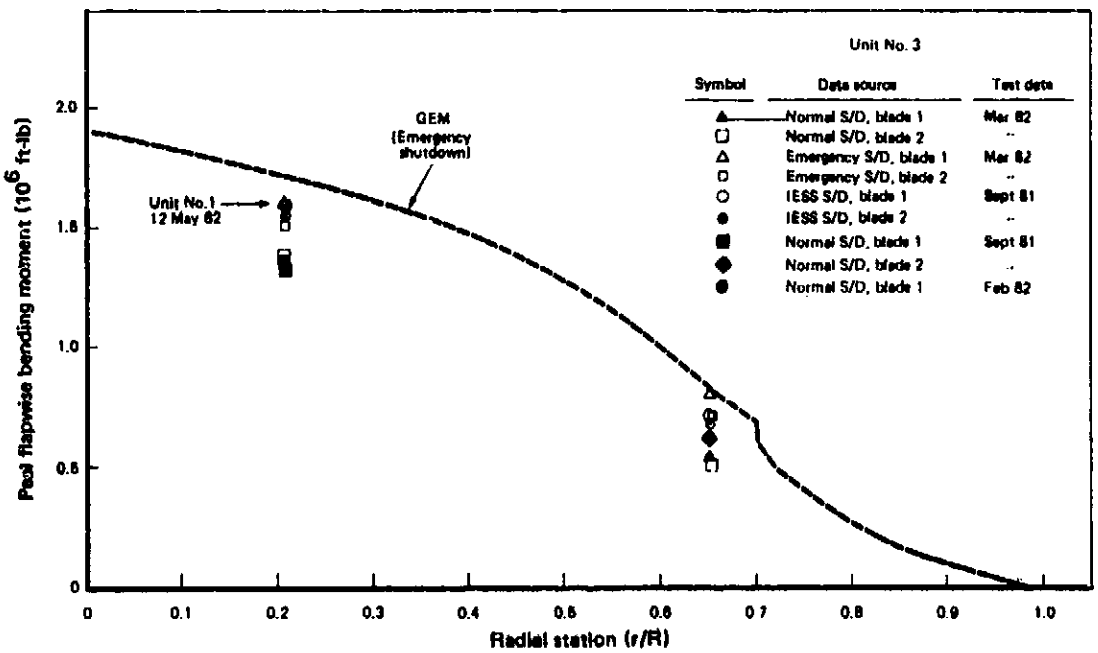

Figure 5-20. Peak Flapwise Bending Moments During Shutdown

Data from all three MOD-2 units exhibit similar shutdown loads. Peak shutdown loads from unit #3 are shown in Figure 5-20 compared to predictions used during the design phase. The shutdown loads predictions are somewhat conservative, but in good qualitative agreement with data. The corres-ponding shutdown time histories are shown in Figures 5-21 and 5-22.

Measured startup loads are small compared to shutdown loads and well within the design loads limits.

5.2.1.2 360 Joint Redesign

The original design of the 360 joint provided lips at the inner and outer peripheries of the flanges to facilitate accurate shimming of the joint during assembly. Distortion due to welding, and machining tolerance requirements after welding would not support the use of an unshimmed joint. Although the lips were originally planned for only the hub side of the joint, it was necessary, in places, to build up lips on the mid section side of the joint with weld metal in order to maintain the minimum flange thickness during the machining operation. In addition, to facilitating assembly of the joints, the lips caused compression stresses in the fillet region of the joint when the joint was bolted together, thereby improving the fatigue performance of the critical region. However, the resulting springiness of the joint produced unacceptable fatigue stresses in the bolts resulting in early fatigue failures.

Two possible solutions to the problem were considered: 1) the use of larger bolts to reduce fatigue stresses to acceptable levels; and 2) shimming the center of the joint to eliminate the springiness. The first solution required accurate bolt preloads if fatigue problems in the fillet region were to be avoided. The second solution requires accurate shimming if bolt and fillet fatigue problems were to be avoided. The second solution was adopted to have the greatest probability of success.

In order for the shimming solution to work, a very accurate means for measuring the gap and locating the shims was required. The solution to both these problems was to identify the shim location on the hub section with a "magic marker" then join the hub and mid section with sufficient non shrinking plastic gage material in the gap to fill the void in the area the shim would be located. After curing, the sections were separated and the plastic gage (ATACS 5111) was removed. The magic marker lines were visible on the plastic gage, thereby allowing accurate location of the shims. The plastic gage was cut in shim size pieces so the required measure could be made. Analytically, a shim .004 inch thicker than the gap provided acceptable fatigue stresses in both the fillet region and the bolts. The allowable tolerance on thickness was +.0025 and -.0010 inch. Since the initial installation was to use peel shims, the additional compliance caused by the glue lines (between laminations) needed to be determined. Tests were conducted to determine the required additional thickness and a schedule of shim thickness versus gap measurements was established (this only applies to unit #1 only because #2 and #3 used solid shims). Also, procedures were established by which the effect of taper in the plastic gage could be accounted for in the manufacture of the shim.

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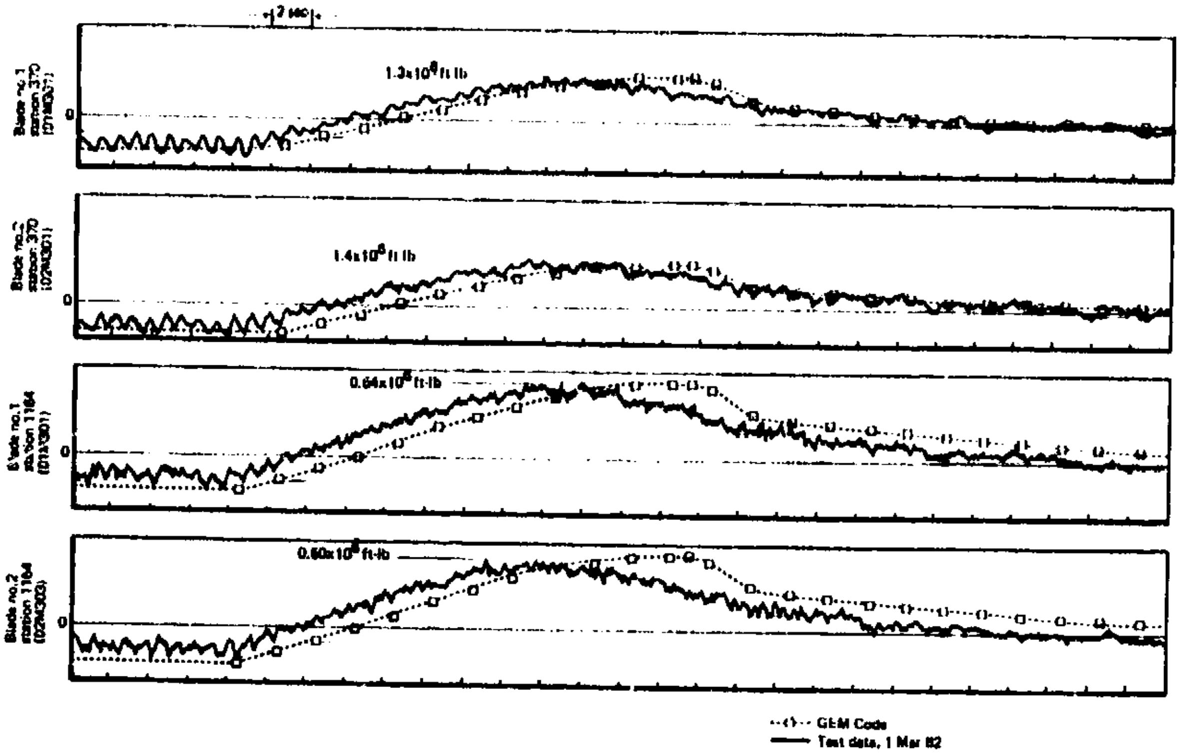

Figure 5-21. Flapwise Bending Moments During Normal Shutdown (WTS Number 3)

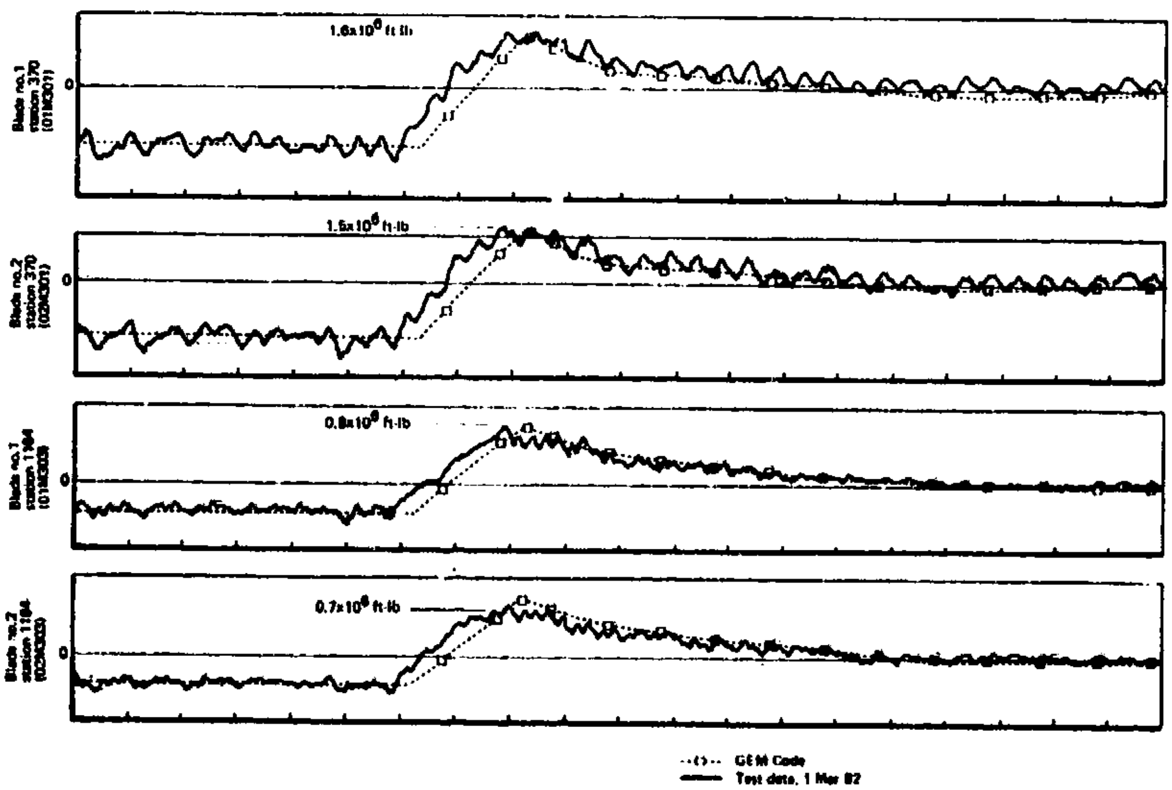

Figure 5-22. Flapwise Bending Moments During Emergency Shutdown (WTS Number 3)

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Because of the high degree of accuracy required in the shimming process, a means by which the final joint integrity could be established was needed. Two different tests were conducted to determine the acceptability of the joints. The first test was a "blueing" test where blueing was applied to the mid section side of the joint. The section was then jointed using the final assembly procedures and then separated. The level of contact of the shims was determined from the amount of blueing transferred. This test was conducted on all three Goldendale units and verified the contact of the shims. Having verified the proper manufacture and application of the shims, the remaining question was whether the shims were functioning in service as predicted analytically. To determine the actual operating stresses in the bolts, four instrumented bolts were installed in unit #1 at Goldendale to measure actual bolt operational stresses. Tests were conducted both to determine the bolt stresses with and without an adjacent bolt missing. A summary of the test results is presented in Figure 5.22A. The test results were in excellent agreement with the analysis and verified the absence of a fatigue problem even if an adjacent bolt was missing or improperly installed. In addition to the instrumented bolts, two fillet regions were also instrumented for this test program. As with the bolts, the fillet stresses were in good agreement with the analysis and verified the absence of a fatigue problem.

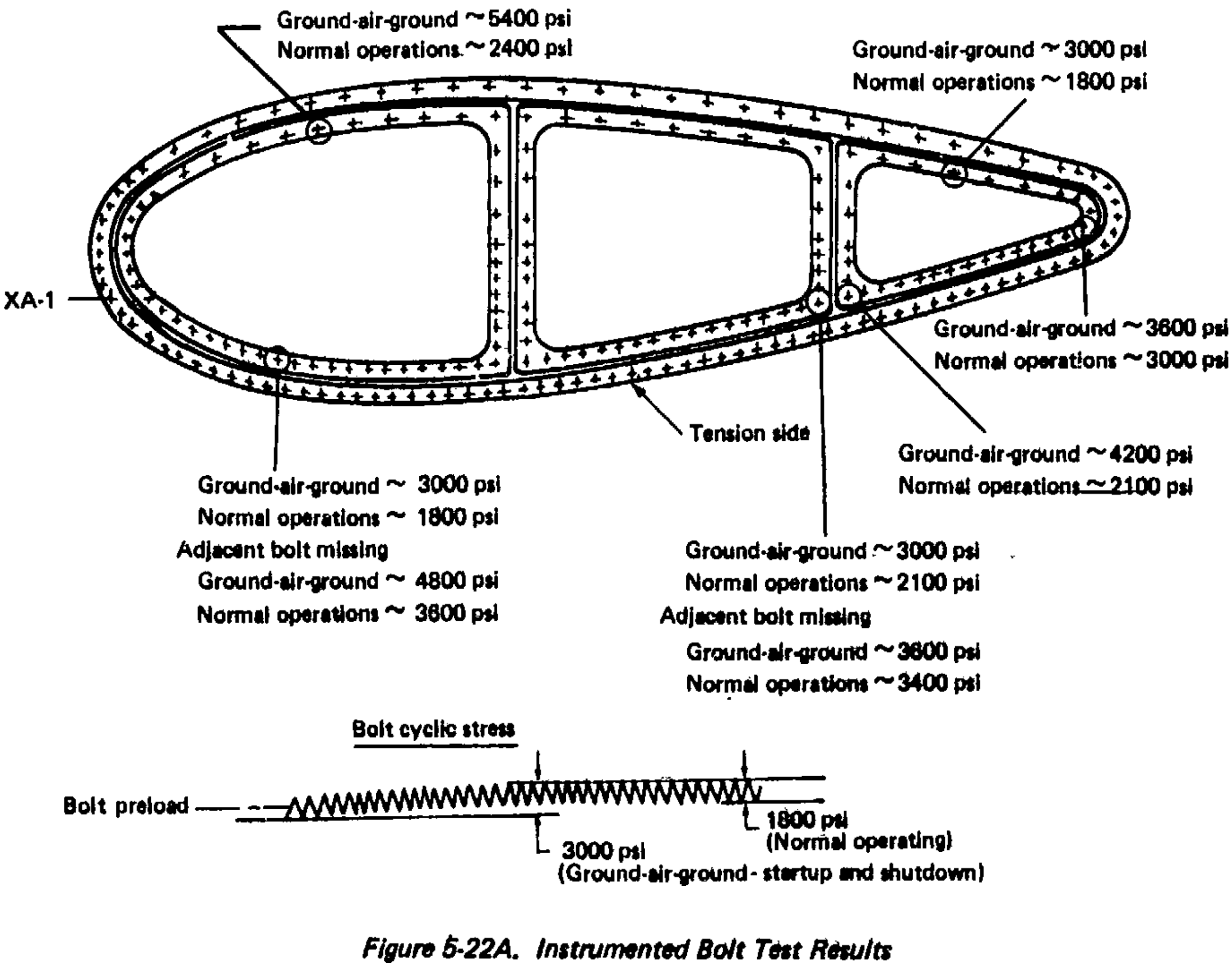

Figure 5-22A. Instrumented Bolt Test Results

5.2.1.3 Pitch Actuator Loads

Proper operation of the pitch actuators is essential to startup, operation and shutdown of the MOD-2 machines. The pitch actuator must have both the required stroke and force capacity over all ranges of operation. The pitch actuator is essentially a linear element which reacts axial loads only. Because of difficulties in instrumenting the actuator rod directly, the head and rod end hydraulic pressures were measured. The actuator forces were calculated from the pressure measurements using the respective head and rod end areas. The relationship between lever arm and collective pitch position was known so that cross plots of pitch actuator moment and collective pitch could be developed from the data.

Figure 5-23 shows the pitch actuator moment during emergency shutdown from an operating condition. This cross plot represents approximately 5 minutes of real time. A positive moment denotes that aerodynamic moments are acting to drive the blade tip toward feather. The scatter of points denoted "operating" represent the normal variation of pitch actuator loads when the rotor is producing power under active pitch control. The mean pitch actuator load is compressive. During shutdown aerodynamic moments are developed which tend to drive the blade tips toward feather causing a tensile load in the actuator. As the blade tips continue to feather and the rotor speed decreases, the primary actuator loads are produced by 1P gravity loading of the blade tips.

The shutdown actuator loads are in good agreement with design loads predictions and within the pitch actuator capability, represented by normal (2,000 psi) and minimum (1500 psi) stall limits. The normal limit represents a zero flow condition. The minimum limit corresponds to a situation in which the hydraulic pressure fluctuations would cause the system pressure to drop sufficiently to trigger a shutdown. Test data shows that the pitch actuator system has sufficient capacity to shutdown the MOD-2 WTS under all normal and fault shutdown conditions.

The pitch actuator moments developed during a startup are illustrated in Figure 5-24. The rotor, starting from a breakaway pitch angle, gradually increases speed. The primary pitch actuator loading is gravity (1P). At a collective pitch of approximately 20° the rotor is under speed control and remains there until synchronization at which point the blade tips drive to the operational pitch schedule. The pitch actuator loads during startup are not critical and well within the pitch actuator design limits.

5.2.1.4 Drive Train Loads

Loads measured on the quill shaft provided a good measure of the drive train loads. The torque and bending moment in two planes were measured. Test data revealed that the quill shaft bending loads were very small (<2 percent of rated torque). The relative flexibility of the quill shaft in relation to the low speed shaft proved very effective in minimizing bending of the quill shaft. Consequently, this section is limited to a discussion of measured quill shaft torques.

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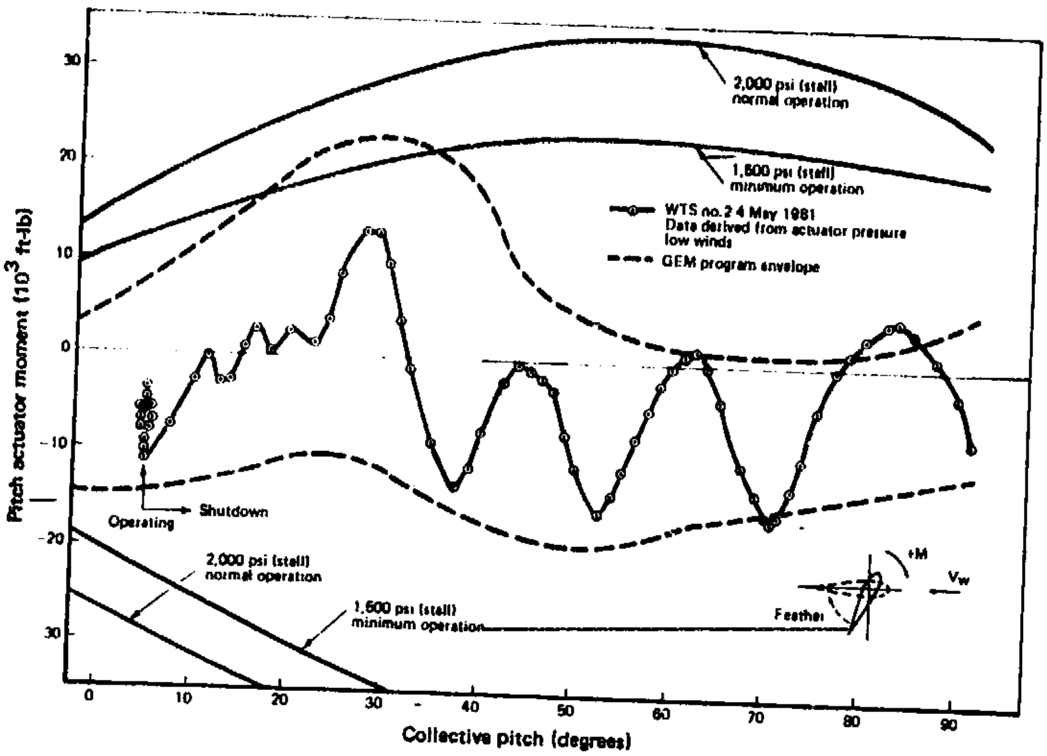

Figure 5-23. Pitch Actuator Moments During Emergency Shutdown

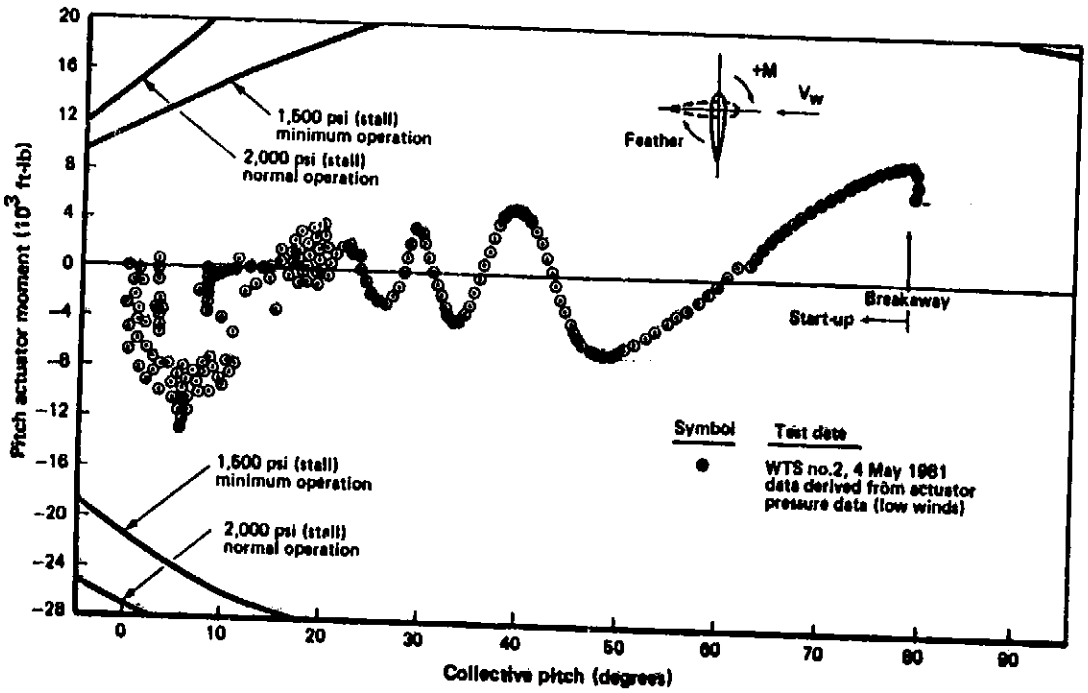

Figure 5-24. Pitch Actuator Moments During Startup

Wind bins analyses were performed on measured quill shaft torques. These data were in good agreement with mean torque design values and the performance data presented in Section 5.1.

Quill shaft cyclic torque is another measure of power quality to which it is directly related. Figure 5-25 shows representative power quality data in the below and above rated modes of operation. Although there were no specific power quality requirements for MOD-2, test data reveal peak cyclic values on the order of 18 percent of rated as shown in Figure 5-25.

Statistical analysis was performed on the cyclic quill shaft torque and presented in the form of a wind bins plot in Figure 5-26. A very conservative estimation of the .999 probability was used in conjunction with the Weibull wind distribution shown in Figure 5-16 to develop the cumulative cyclic torque curve shown in Figure 5-27. The MOD-2 (0.999) design loads exceed measured data whereas the (.50) design loads are unconservative. This difference in the load spectrum does not affect the 30 year fatigue life estimate for the quill shaft as demonstrated in Section 5.2.2.

5.2.1.5 Tower Loads

Tower loads were measured at Sta. 600 above the transition section. Tower torque and bending in two orthogonal directions were monitored. Statistical analysis was performed on tower cyclic loads in a manner similar to other loads channels.

A wind bins plot of cyclic tower torque is shown in Figure 5-28. Tower torque is insignificant to tower design compared to bending loads but relevant to the design of the yaw drive system. During yawing the parking brakes are relaxed and all yaw torque is reacted through the yaw drive system. The measured cyclic yaw moments, inferred from the tower torque data, exceed MOD-2 yaw drive cyclic loads. A yaw motor case failure has recently occurred on Unit #5 (Solano). Although the case has been shown to be understrength, it is unclear to what extent higher than predicted loads contributed to the failure. A yaw loads test program is in progress at Goldendale to assess the problem.

Statistical analyses were performed on the cyclic tower moments as shown in Figure 5-29. Statistical analyses were done separately on each bending moment channel and statistics combined vectorally for each wind bin. This is equivalent to assuming bending loads from the two channels are always in phase. Test data time history reveal that this is not strictly correct and results in a somewhat conservative estimate of the total cyclic moment. A conservative (0.999) cyclic loads estimate was combined with the design Weibull distribution of mean winds to develop the cumulative loads plot shown in Figure 5-30. The test data exceeds the MOD-2 design loads, the implications of which are discussed in the tower fatigue life analysis of Section 5.2.2.

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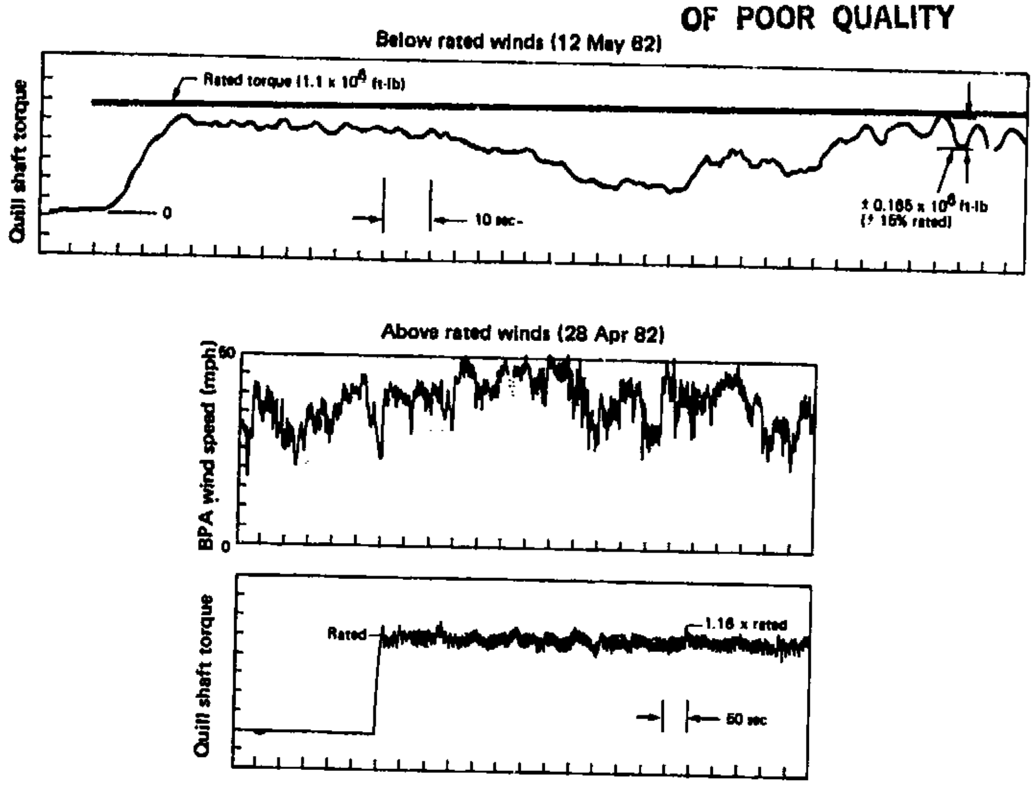

Figure 5-25. Quill Shaft Torque Time Histories

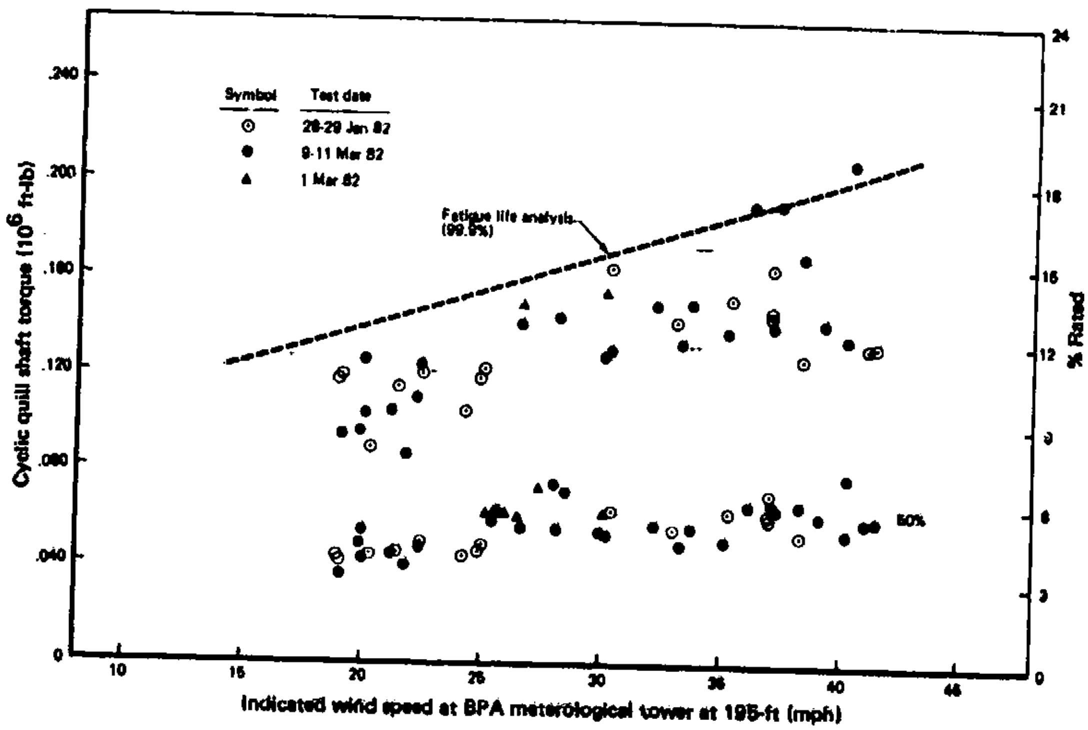

Figure 5-26. Cyclic Quill Shaft Torque (WTS Number 3)

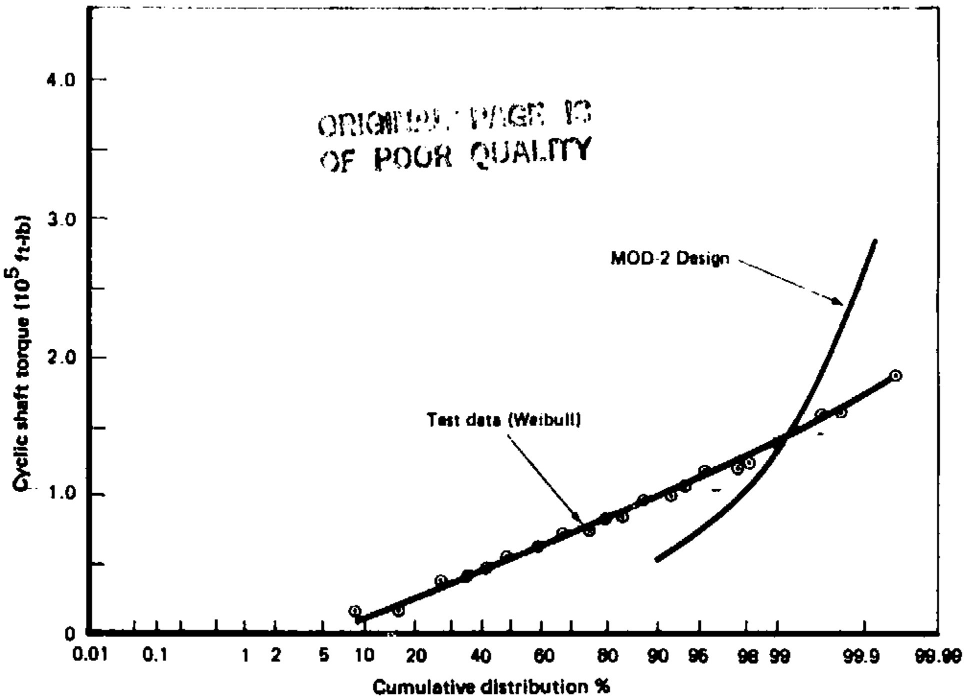

Figure 5-27. Cumulative Probability Cyclic Quill Shaft Torque

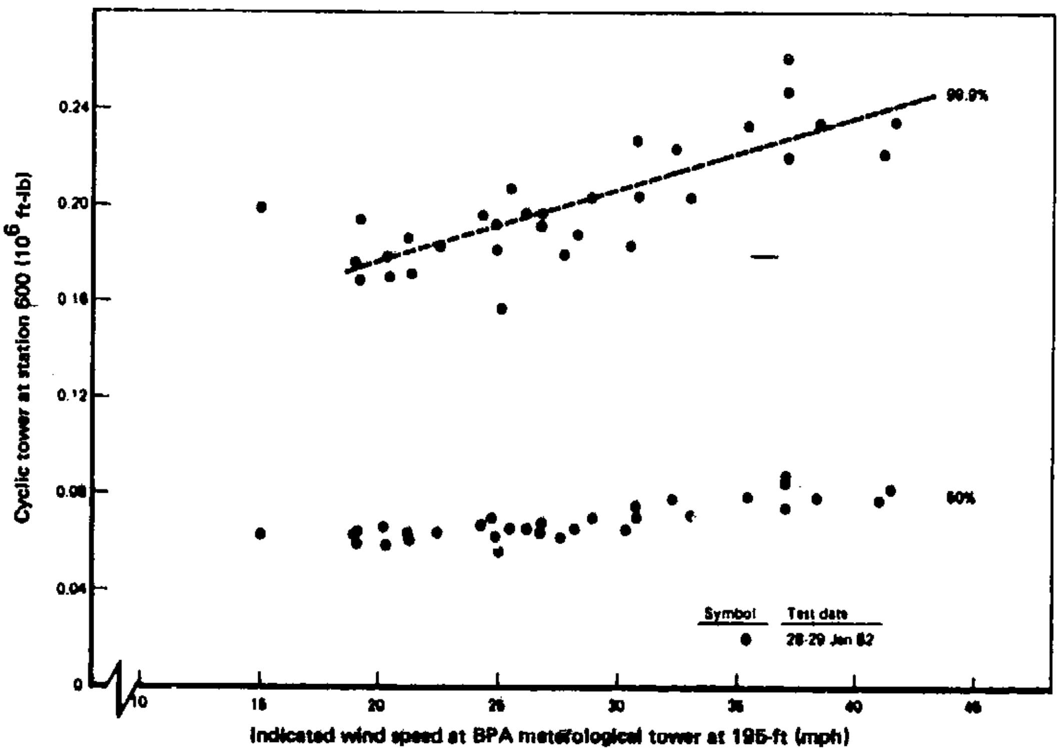

Figure 5-28. Cyclic Tower Torque at Station 600 (WTS Number 3)

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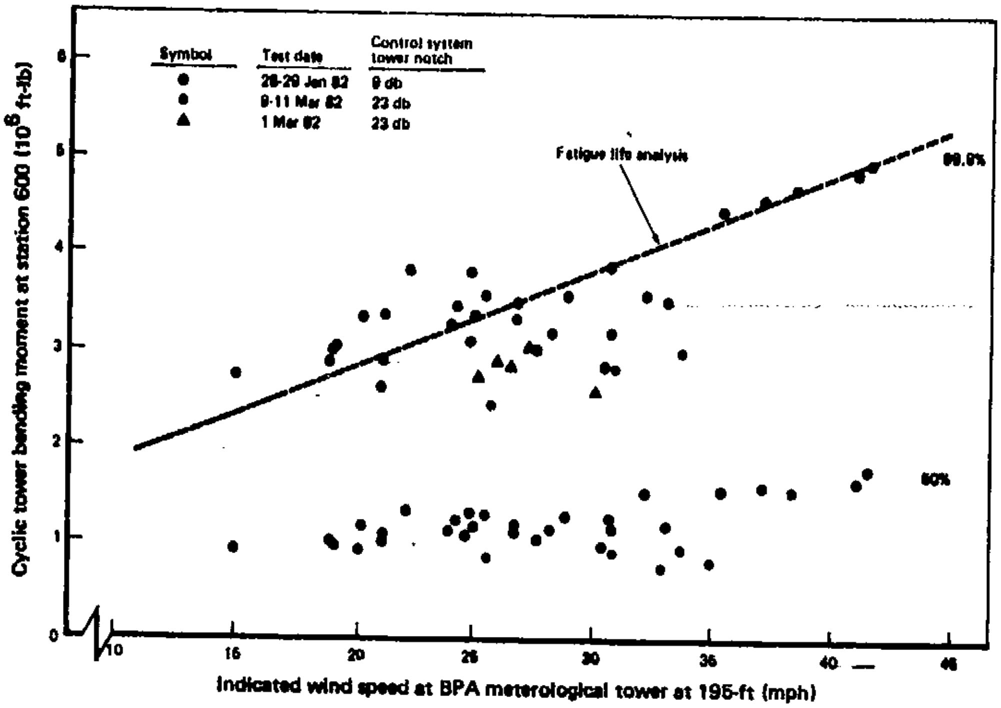

Figure 5-29. Cyclic Tower Bending Moments at Station 600 (WTS Number 3)

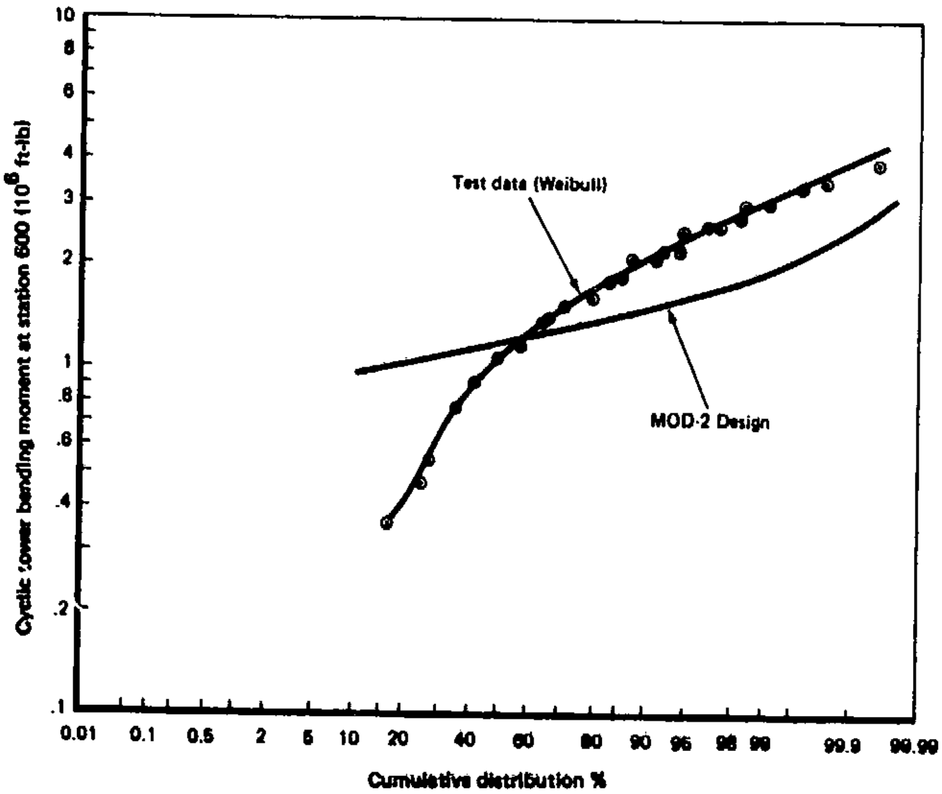

Figure 5-30. Cumulative Probability of Cyclic Tower Bending Moment at Sta. 600

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5.2.1.6 Teeter Motion

Unsteady wind conditions including variable wind gradients and wind direction result in a 1 per rev cyclic teeter response. The response amplitudes increase with wind speed and yaw heading error. Figure 5-31 shows the measured peak cyclic teeter response compared to the MOD-2 design envelope. The data includes only teeter response measured while operating. Teeter response of all Goldendale MOD-2 units was similar. Except at low winds, the teeter response falls within the design envelope. The cumulative probability distribution of cyclic teeter motion based on the design Weibull distribution of mean winds is well within the design spectrum. Measured peak cyclic teeter motions do not exceed 5°. There has been no evidence of impacting the teeter stops at 6.5° while operating.

During startup and shutdown, transient cyclic teeter motions were measured. Under these conditions the teeter brake is applied below 8 rpm. Figure 5-32 shows the maximum cyclic teeter angles observed for a number of startups and shutdowns under a variety of wind conditions. The average (50 percent) maximum teeter response was 3.1° during startup and 2.3° during shutdown. Impacting of stops during these transient conditions was not observed. The cumu-lative probability distribution shown in Figure 5-32 also suggests that the probability of impacting the stops is remote.

Near the end of the acceptance test program, the teeter brakes were deactivated so that the requirements for the brakes could be assessed. The teeter stop stress gage instrumentation was load-calibrated and about five hours of parked rotor teeter motion and impact load data were acquired. Wind speeds varied from 37 mph up to 52 mph, with teeter velocities at the instant of stop contact varying from about .7° per second to 1.8° per second. Analysis of this data indicated that excessive loads may be encountered. Because of these indications, data to be acquired throughout the rest of the planned test program must be reviewed before a final recommendation can be made. In the interim, the brakes are disabled because their current capacity does not eliminate the critical load condition, and disabling the brake does not present a significant risk to the machine.

5.2.1.7 Nacelle Vibration

The vibration environment in the nacelle was measured to assess whether drive train, gearbox, generator and control system environments were within design limits. Accelerometers were mounted on the low speed shaft bearing supports, gearbox and generator.

The acceleration spectra measured at various locations in the nacelle during above rated operation are shown in Figure 5-33. The measured vibration environments are low compared to the MOD-2 nacelle vibration design envelope. The primary excitation is harmonic motion at 1P, 2P and 4P and at the generator frequency. There was no evidence that any drive train excitation frequencies were coupling with mount or nacelle structural modes. The measured gearbox and generator vibrations are within the Stal-Laval gearbox vibration criteria and NEMA standards respectively.

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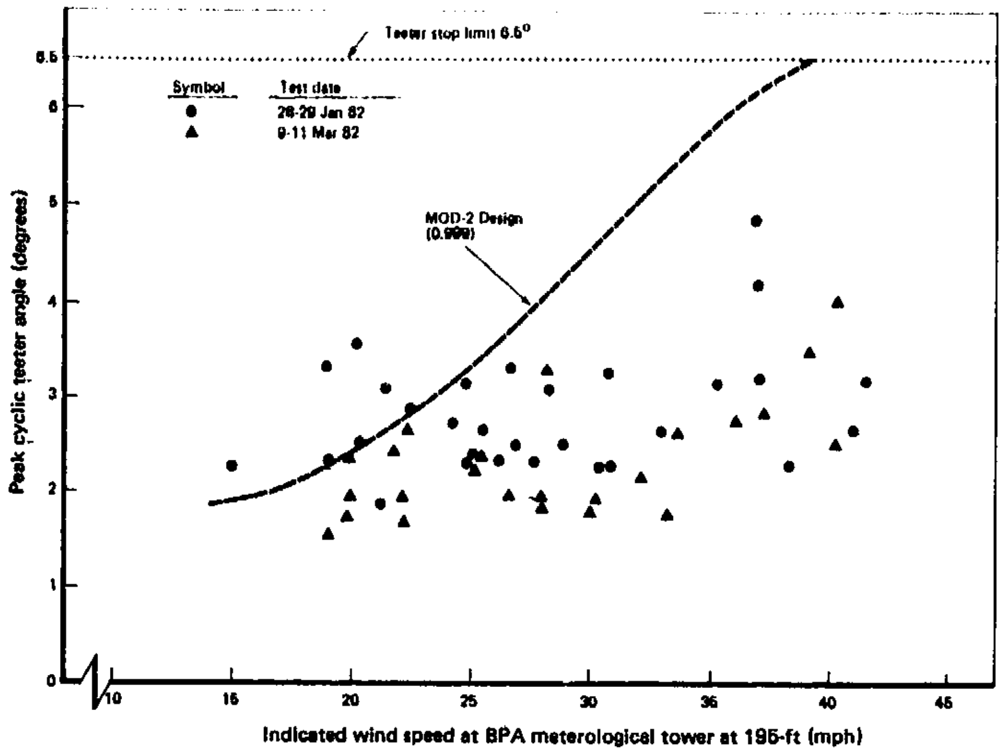

Figure 5-31. Cyclic Teeter Angle During Operation (WTS Number 3)

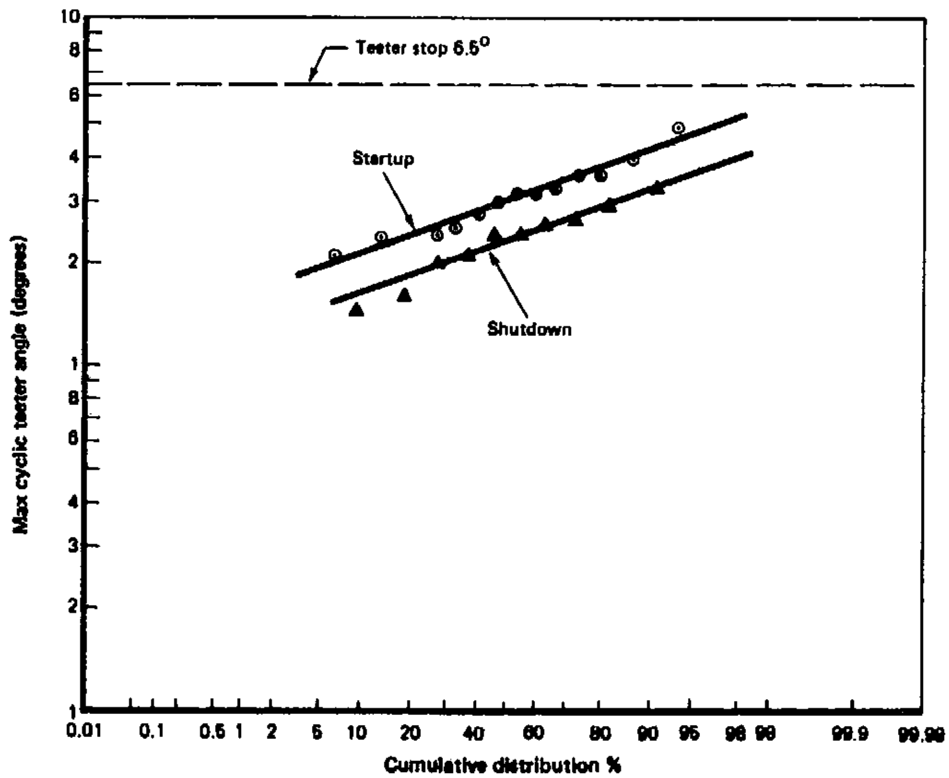

Figure 5-32. Cumulative Probability of Cyclic Teeter Angle During Startup and Shutdown

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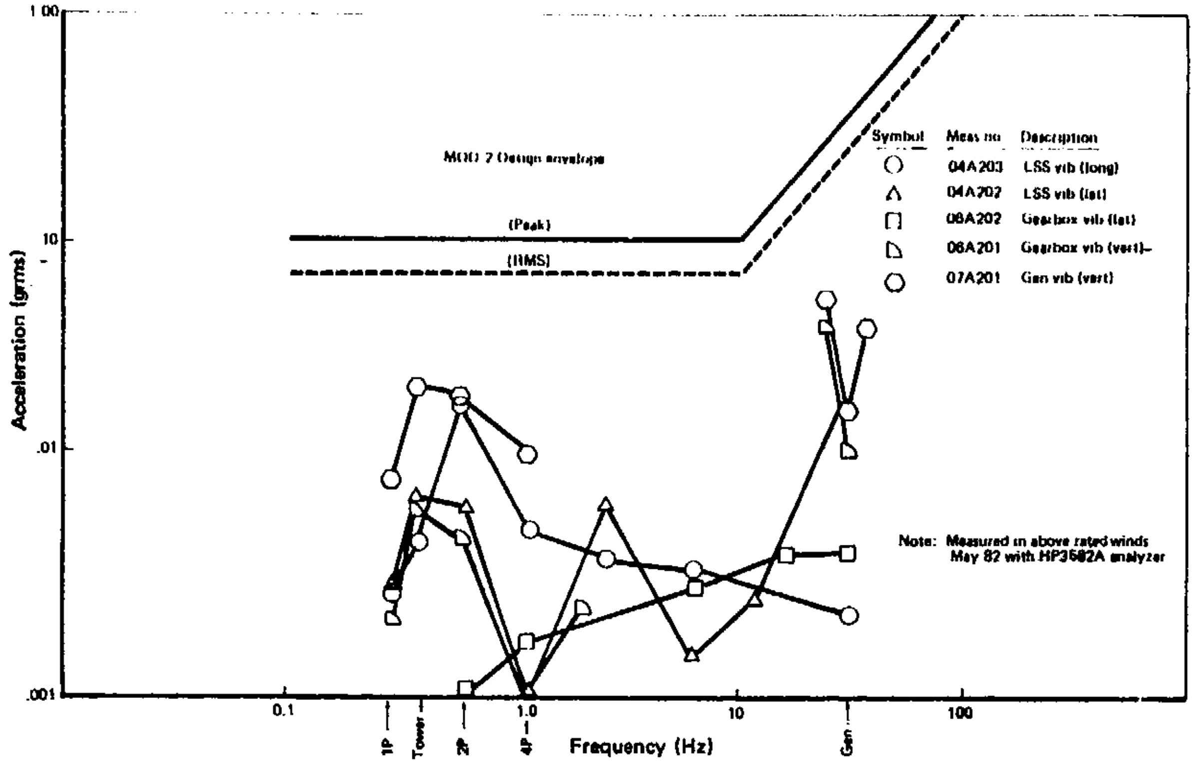

Figure 5-33. Nacelle Acceleration Spectrum During Above Rated Operation (WTS Number 2)

5.2.2 Fatigue Life Assessment

The purpose of this section is to present an assessment of the fatigue life based on the measured loads at Goldendale. The basic procedure used to calculate fatigue life is presented in the MOD-2 Wind Turbine System Concept and Preliminary Design Report (Reference 1). Both the design criteria Weibull wind speed distribution and the as-measured Goldendale wind speed distribution were considered in the determination of fatigue life. The anticipated fatigue life of the major components is discussed separately in the following sections. The term fatigue life when applied to the rotor and tower structure is actually the mean time between repairs. When a fatigue crack develops in either of these structures, it can be repaired and the structure returned to service.

5.2.2.1 Rotor Fatigue Assessment
For the original design, the fatigue load spectrum was derived from the MOSTAB load calculations. Since the measured fatigue cyclic flapwise loads were higher than design values, it was necessary to derive a new load spectrum. Figure 5-34 outlines the procedure by which the fatigue spectrum was derived.

The procedure was to:

1) Divide the wind speed distribution into wind bins;
2) Determine the total cycles in each wind bin by assuming 17.5 cycles/minute (1 cycle per revolution);
3) From the plot of wind speed versus flap moment, determine the average mean and average 99.9% cyclic moment for each wind bin;
4) Assuming (as indicated by the test data) the 50 percent cumulative probability alternating flap moment to be 1/3 of the 99.9 percent cumulative probability alternating flap moment, determine the distribution of alternating flap moment for each wind bin.
5) Add for each wind bin, the centrifugal load and the mean flap load, and superimpose the alternating chord and flap loads assuming they are in phase.

The above load spectrum was then used to calculate a stress spectrum at various points at each chordwise weld station. The stress spectra were then used in the assessment of the fatigue life capability (time between repairs).

Fatigue life as presented in Figures 5-35 thru 5-42 and Table 5-1 is for the Weibull wind speed distribution. The calculations are based on 1) nominal gage thickness, 2) no allowances for secondary "out of contour" stresses, 3) design MOSTAB mean loads, and 4) average measured cyclic loads. Whereas the nominal gage thickness assumption is conservative, ignoring secondary out-of-contour stresses is unconservative. The fatigue life for the rotor welds is initially presented based on the design criteria flaw size (.050 inch deep by .250 inch long) and then the flaw size consistent with a 30 year life is presented. The design criteria flaw size was selected as a conservative estimate of the worse size that should ever escape detection. Per the inspection/acceptance criteria, all cracks (regardless of size) and all other defects 0.125 inch or longer are rejectable. The rationale for using 0.250 inch as a design value was to provide a degree of conservatism between the design and inspection flaw size because no other factors were being applied to the fatigue allowables. Figure 5-43 and Table 5-2 present the anticipated fatigue life for the Goldendale wind speed distribution. The Goldendale wind speed distribution is significantly less severe than the Weibull

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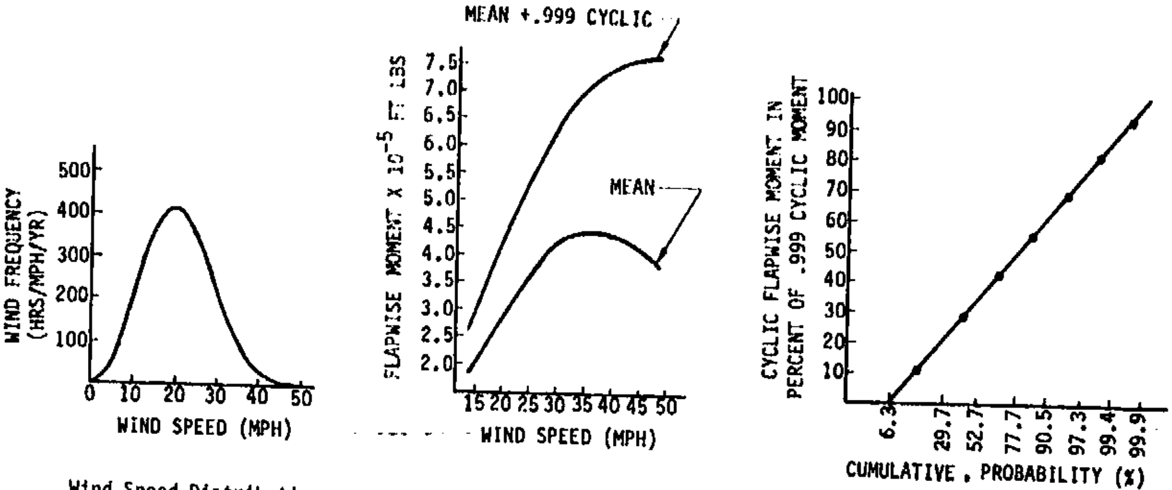
Data Input: Wind Speed Distribution, Centrifugal Force, Chordwise Load, Flapwise Loads (Flapwise Load Varies with Wind Speed)



Wind Speed Distribution

Variation in Flap Loads with Wind Speed

Cumulative Probability of Alternating Flap Loads

Procedure:
1) Divide wind distribution to get distribution of flap alternating mounts
2) Use cumulative probability to get distribution of flap alternating mounts
3) Add centrifugal stress to mean flap stress and phase flap alternating with chord assuming a 1 per rev alternating load

Figure 5-34. Fatigue Spectrum Derivation

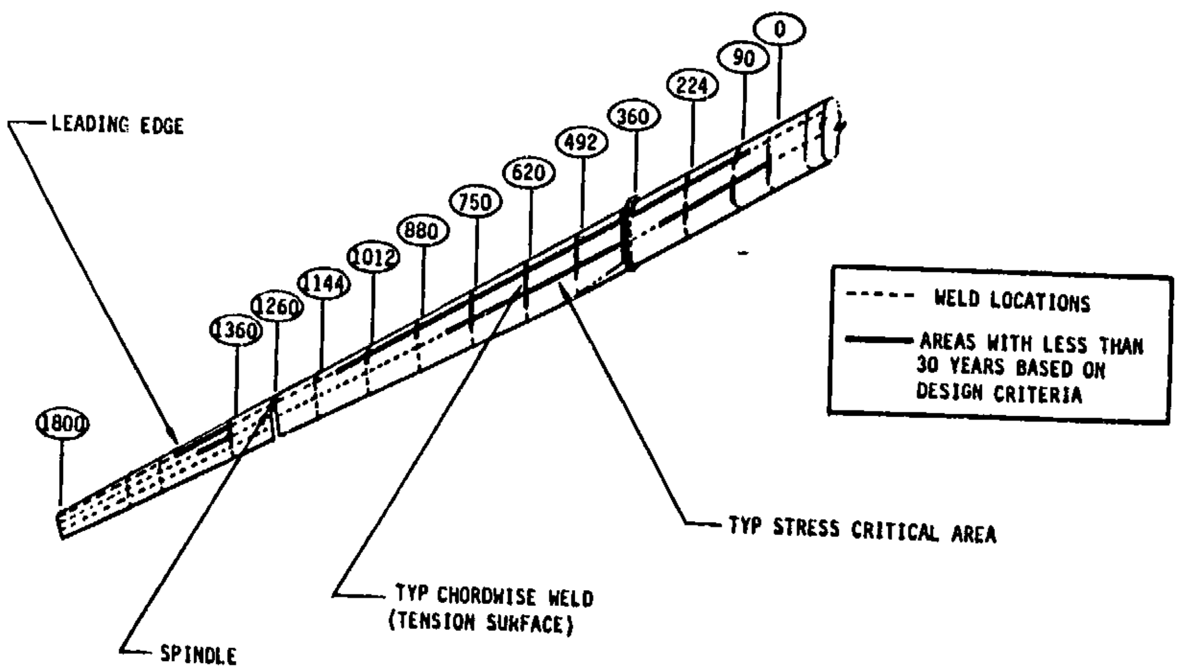


Figure 5-35. Weld Areas of Concern - Weibull Wind Speed Distribution

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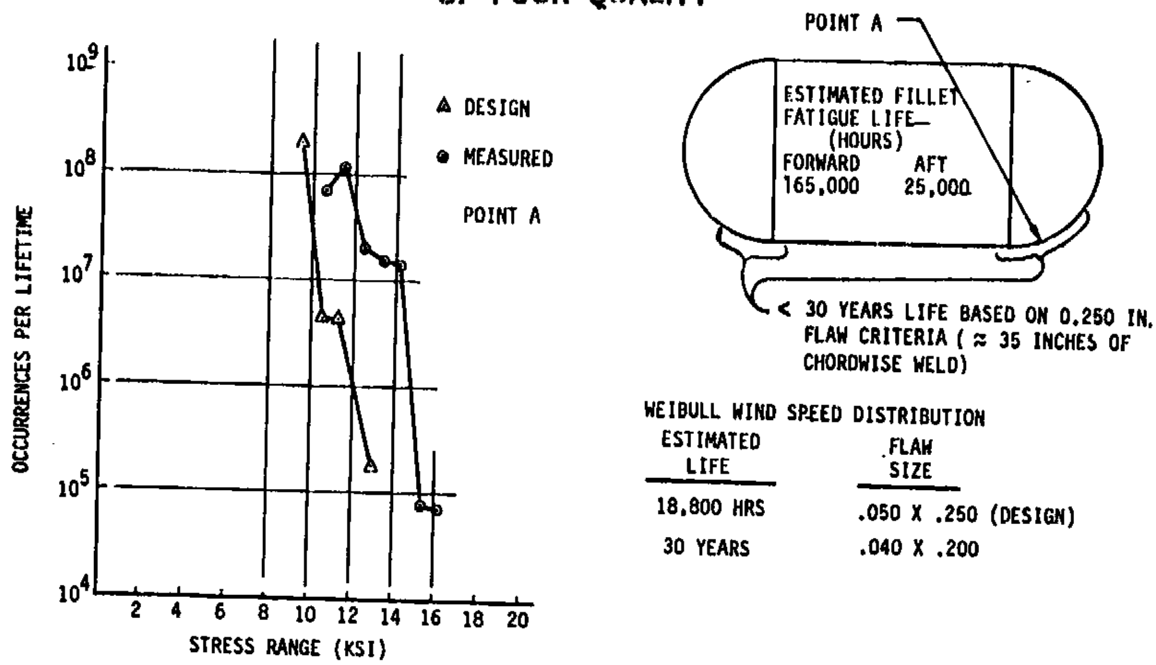

Figure 5-36. Rotor Fatigue Status - Station 91

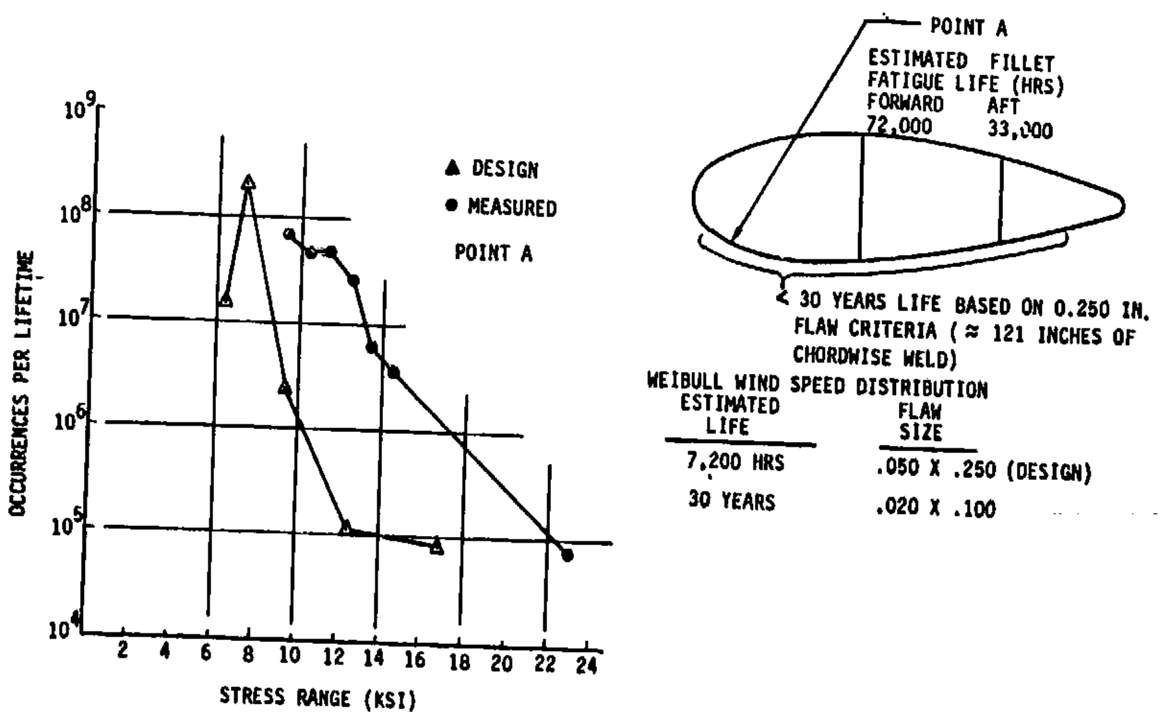

Figure 5-37. Rotor Fatigue Status - Station 363

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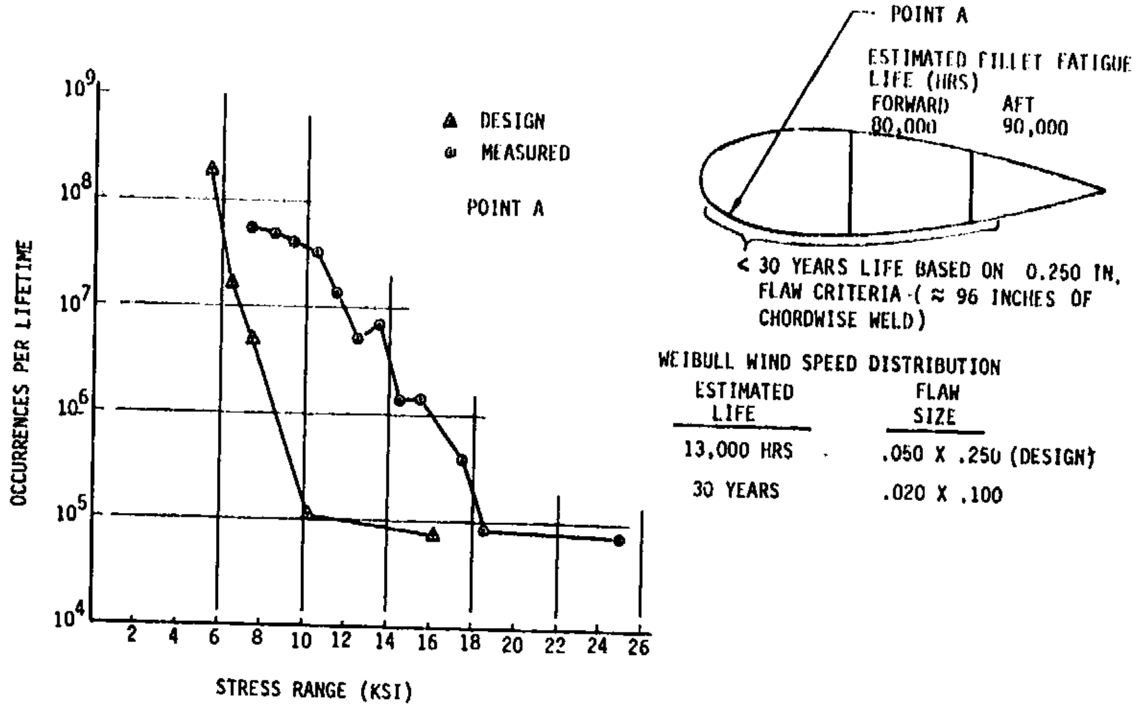

Figure 5-38. Rotor Fatigue Status - Station 620

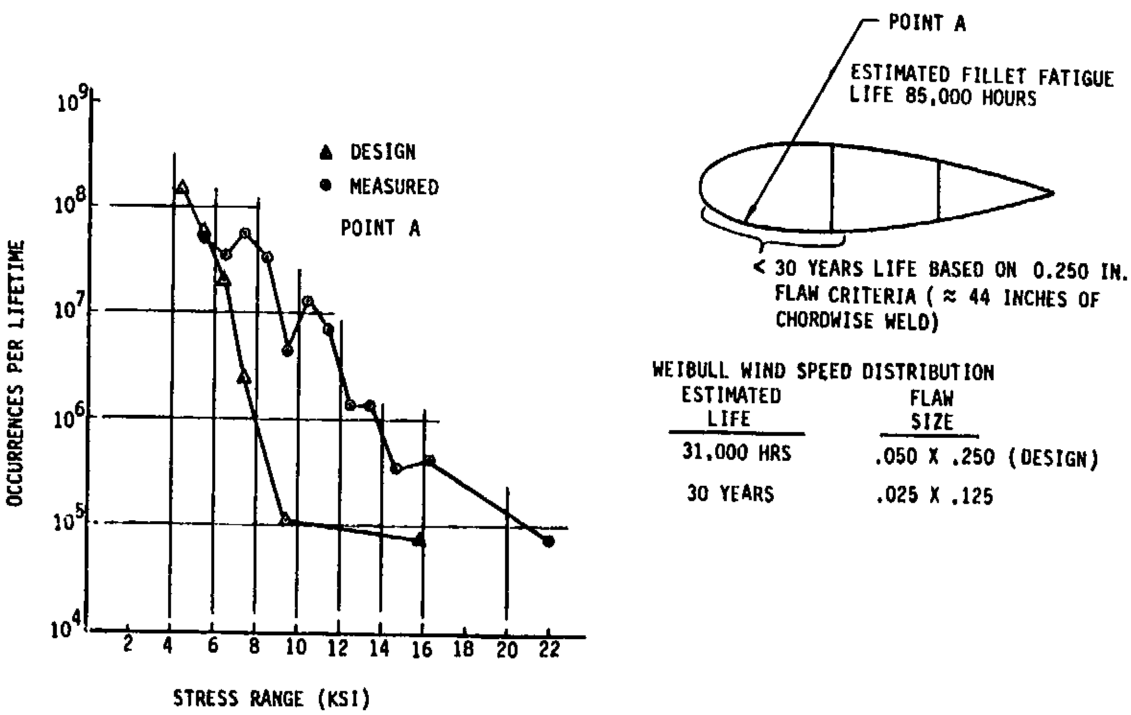

Figure 5-39. Rotor Fatigue Status - Station 880

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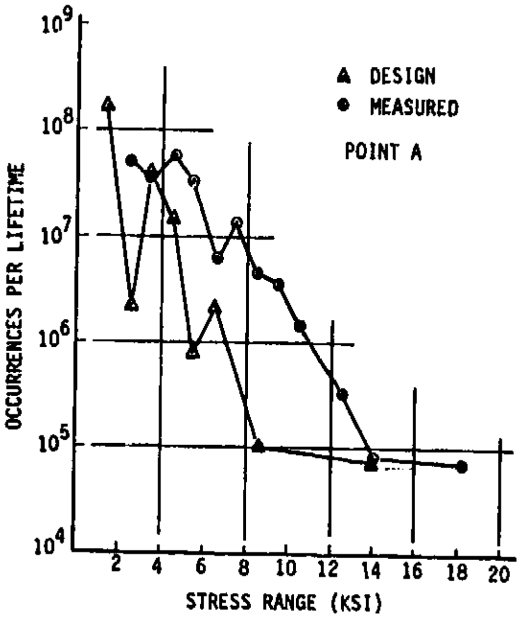
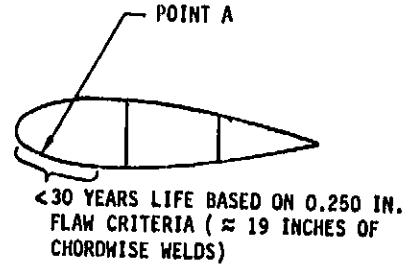
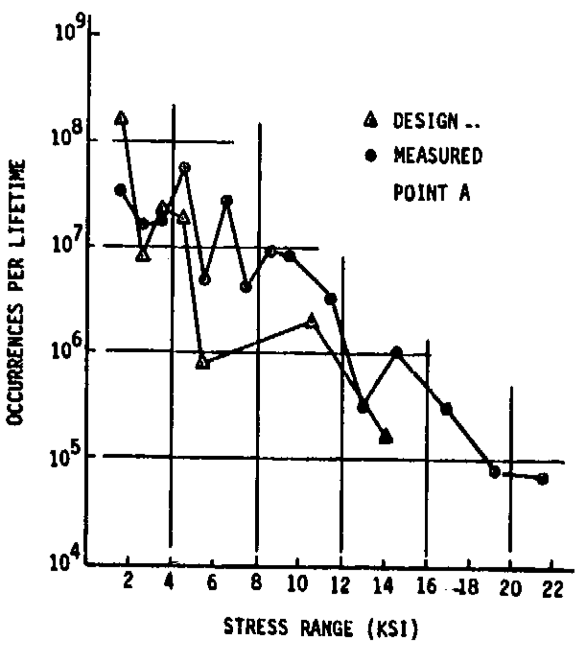


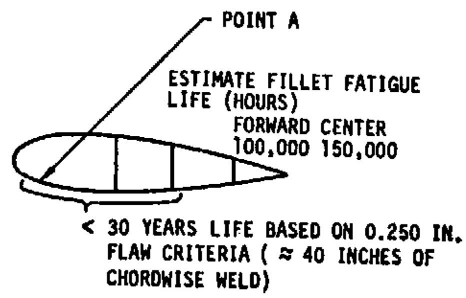


WEIBULL WIND SPEED DISTRIBUTION

ESTIMATED LIFE	FLAW SIZE
150,000 HRS	.050 X .250 (DESIGN)
30 YEARS	.045 X .225

Figure 5-40. Rotor Fatigue Status - Station 1144





WEIBULL WIND SPEED DISTRIBUTION

ESTIMATED LIFE	FLAW SIZE
90,000 HRS	.050 X .250 (DESIGN)
30 YEARS	.041 X .205

Figure 5-41. Rotor Fatigue Status - Station 1360

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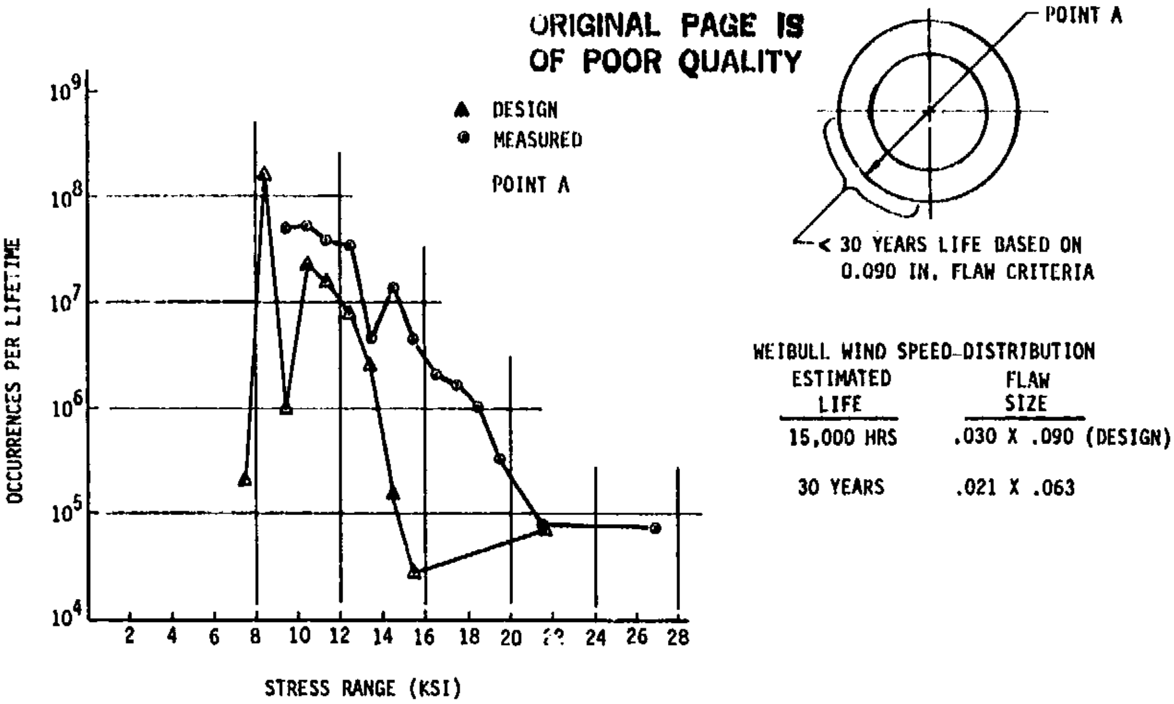

Figure 5-42. Rotor Fatigue Status - Spindle

Table 5-1. Summary Rotor Fatigue Status – Weibull Wind Speed

ROTOR STATION	ESTIMATED LIFE BASED ON ORIGINAL CRITERIA	LENGTH OF [1] CHORDWISE WELD WITH < 30-YEAR LIFE	FLAW SIZE FOR 30-YEAR LIFE DEPTH X LENGTH	COMMENTS
0	12,000 HRS. (1.7 YRS.)	20 IN.	.039 X .195 IN.	FILLET WELDS AT AFT SPAR < 30-YEAR LIFE (28,000 HRS)
91	18,800 HRS. (2.7 YRS.)	35 IN.	.040 X .200 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (25,000 HRS)
224	23,500 HRS. (3.4 YRS.)	56 IN.	.040 X .200 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (120,000 HRS)
357	16,900 HRS. (2.5 YRS.)	42 IN.	.030 X .150 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (75,000 HRS)
363	7,200 HRS. (1.0 YRS.)	121 IN.	.020 X .100 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (33,000 HRS)
492	12,800 HRS. (1.9 YRS.)	72 IN.	.023 X .115 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (70,000 HRS)
620	13,000 HRS. (1.9 YRS.)	96 IN.	.020 X .100 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (80,000 HRS)
750	21,400 HRS. (3.1 YRS.)	67 IN.	.023 X .115 IN.	FILLET WELDS AT AFT AND FORWARD SPAR < 30-YEAR LIFE (85,000 HRS)
880	31,000 HRS. (4.5 YRS.)	44 IN.	.025 X .125 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (85,000 HRS)
1012	51,800 HRS. (7.5 YRS.)	32 IN.	.030 X .150 IN.	FILLET WELDS AT FORWARD SPAR < 30-YEAR LIFE (120,000 HRS)
1144	150,000 HRS. (21.8 YRS.)	19 IN.	.045 X .225 IN.	FILLETS O.K.
1360	90,000 HRS. (13.1 YRS.)	40 IN.	.041 X .205 IN.	FILLET WELDS AT FORWARD AND MIDDLE SPAR < 30-YEAR LIFE (100,000 HRS)
SPINDLE	15,000 HRS. (2.2 YRS.)	≈ 20% OF CIRCUMFERENCE	.021 X .063 IN.	

TOTAL WELD LENGTH WITH < 30-YEAR LIFE CHORDWISE 106 FT. SPANWISE 330 FT.

[1] **Life = Mean time between repairs**

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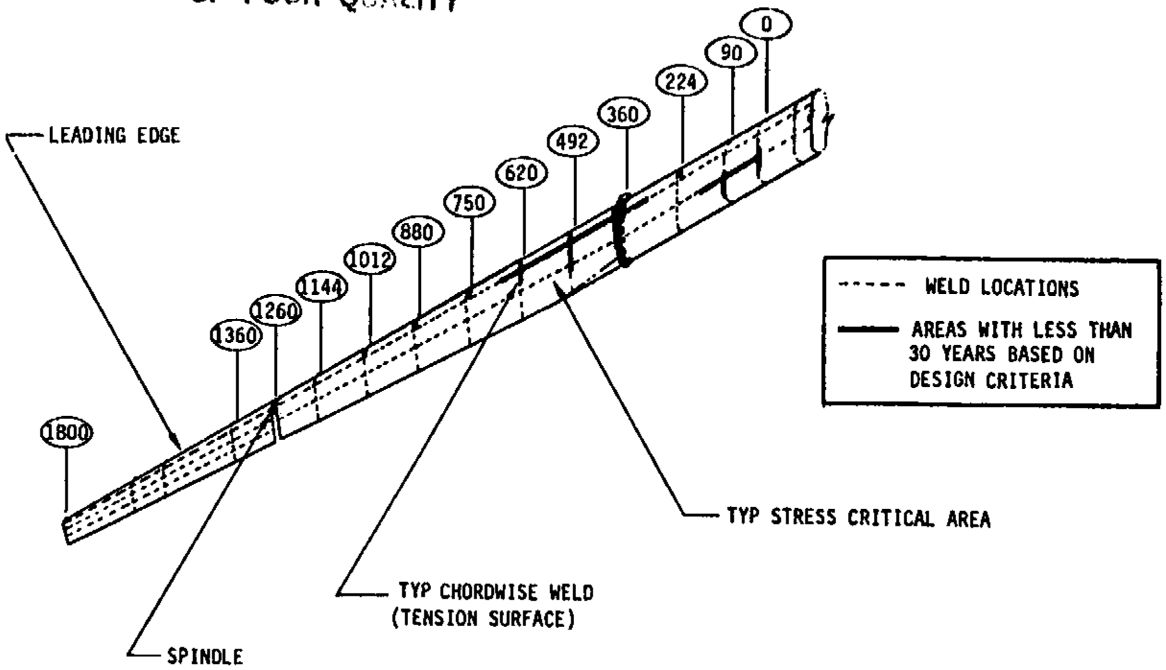

Figure 5-43. Weld Areas of Concern - Goldendale Wind Speed Distribution

Table 5-2 Summary of Rotor Status—Goldendale Wind Distribution

LOCATION	ESTIMATED FATIGUE LIFE [1]	COMMENTS
STATION 0	3.4 YRS (15,300 HRS)	FILLET WELDS AT AFT SPAR < 30 YEAR LIFE (56,000 HRS)
STATION 91	5.4 YRS (24,600 HRS)	FILLET WELDS AT AFT SPAR < 30 YEAR LIFE (56,000 HRS)
STATION 224	7.0 YRS (32,000 HRS)	FILLET WELDS OK
STATION 357	4.7 YRS (21,400 HRS)	FILLET WELDS AT FORWARD SPAR < 30 YEAR LIFE (140,000 HRS)
STATION 363	1.8 YRS (8,100 HRS)	FILLET WELDS AT FORWARD AND AFT SPAR < 30 YEAR LIFE (60,000 HRS)
STATION 492	3.5 YRS (15,800 HRS)	FILLET WELDS AT FORWARD AND AFT SPAR < 30 YEAR LIFE (130,000 HRS)
STATION 620	3.5 YRS (15,800 HRS)	FILLET WELDS AT FORWARD SPAR < 30 YEAR LIFE (145,000 HRS)
STATION 750	6.4 YRS (29,000 HRS)	FILLET WELDS OK
STATION 880	9.6 YRS (44,000 HRS)	FILLET WELDS OK
STATION 1012	20.0 YRS (90,000 HRS)	FILLET WELDS OK

[1] Life = Mean time between repairs

distribution. Because of the less severe environment at Goldendale, the extent of the areas with negative margins is dramatically reduced. For the worst area (Station 363), the 30 year flaw size is 0.030 inch deep by 0.150 inch long. Additionally the spindle region has 30 year life based on the original criteria with the Goldendale distribution.

Because of the crack detection system, the rotor is a failsafe structure. Fatigue life therefore is actually the time between anticipated repairs. For Goldendale, if the inspection/acceptance criteria was successful in detecting and repairing defects greater than 0.125 inch, the rotor should have a 30 year life if the out-of-contour stresses are low. If the out-of-contour stresses are high and defects are present in the high stress area or if defects greater than 0.125 were missed, there will be a need for inservice repairs. The spindle is not failsafe because the crack detection system does not protect it. However, it has a 30 year life for the Goldendale loads.

5.2.2.2 Pitch Actuator Fatigue Assessment

The measured fatigue loads are within the design limits, therefore the anticipated fatigue life for the pitch actuator is 30 years.

5.2.2.3 Drive Train Fatigue Assessment

The only component in the drive train for which the measured loads were different than the design loads was the quill shaft (Figure 5-27). The load spectrum for the quill shaft utilized the MOSTAB design mean load values and the measured cyclic values. Figure 5-44 provides a comparison of the measured versus design stresses for the quill shaft. Since the quill shaft satisfied the 30 year life requirement with the Weibull wind speed distribution, the Goldendale distribution was not considered.

5.2.2.4 Tower Fatigue Assessment

The fatigue life assessment of the tower used the design mean loads and the measured alternating loads. For the tower, the wind direction was assumed to be constant. Based on the wind direction data from Goldendale, the assumption of a constant wind direction is not excessively conservative. The design mean loads in conjunction with the measured cyclic loads were used in construction of the stress spectra. Nominal gage thicknesses with no allowance for secondary out-of-contour stresses were used in the determination of the stress values. Figure 5-45 presents the assessment of the tower fatigue life for both the Weibull and Goldendale wind speed distribution. For the tower, the design flaw size was taken to be 1.5 times the acceptable defect size. Since the acceptance criteria for the tower was per the AWS requirements, the defect size of concern varies with the wall thickness. The 1.5 factor was used rather than the 2 factor because the size flaws allowed by AWS are large and the chance of missing the defects is small. For the Goldendale wind distribution, there are only two weld seams with less than 30 years life. For these two, the minimum life is 20 years. Periodic inspection can be used on the tower to detect incipient crack propagation and repair before failure.

5.2.2.5 Fatigue Assessment Summary

In summary, the differences between measured and design loads have caused several

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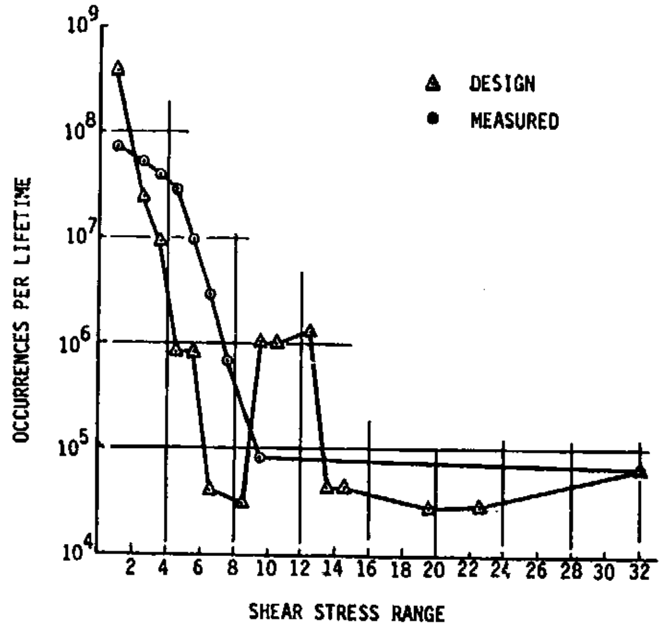
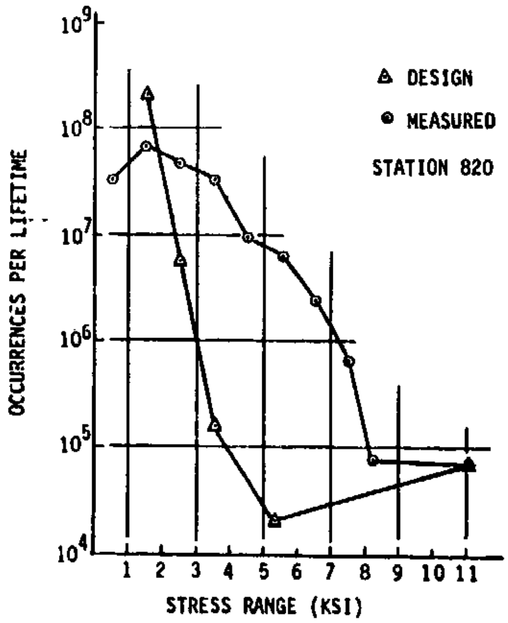
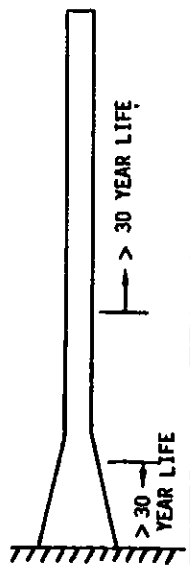


ESTIMATED LIFE	FLAW SIZE
30 YEARS	0.016 X .080 (DESIGN)

Figure 5-44. Quill Shaft Fatigue Status





WEIBULL WIND SPEED DISTRIBUTION

ELEVATION	ESTIMATED LIFE [1] HRS	ESTIMATED LIFE [1] YRS	INCHES OF WELD WITH < 30 YEAR LIFE
410	120,000	17.7	65 INCHES
500	72,000	10.5	80 INCHES
600	120,000	17.7	60 INCHES
700	69,000	10.0	80 INCHES
820	82,000	12.0	75 INCHES
940	120,000	17.4	55 INCHES
1060	129,000	18.8	50 INCHES

GOLDENDALE WIND SPEED DISTRIBUTION

ELEVATION	ESTIMATED LIFE [1] HRS	ESTIMATED LIFE [1] YRS	INCHES OF WELD WITH < 30 YEAR LIFE
500	113,000	25	35
700	90,000	20	45

[1] Life = Mean time between repairs

Figure 5-45. Tower Fatigue Status

areas in both the rotor and tower to have less than 30 years life if the original design criteria is applied. At Goldendale, the actual environment is not as severe as the design, therefore, the problem areas are significantly reduced. The rotor has the minimum anticipated life, however, it is a failsafe structure because of the crack detection system. The tower is not a failsafe system, however a reasonable inspection criteria can be formulated to preclude a catastrophic failure. Therefore, although some repair problems may occur, periodic inspections on the tower and the crack detection system on the rotor allow the machines at Goldendale to be operated without fear of a catastrophic failure.

5.3 Mechanical System Performance

5.3.1 Rotor Pitch Control Hydraulic System

The rotor pitch control hydraulic system is designed to control blade tip motion during normal WTS operation, and rotate blade tips to the feather position for system shutdown. Testing has shown that the system is capable of meeting the maximum required blade pitch rate of 1.0° per second sustained motion and 4.0° per second for at least six seconds, with emergency shutdown response of between 4.0° and 8.0° per second. The pitch hydraulic system consists of standard, off the shelf, hydraulic components, with the exception of a special hydraulic reservoir. This reservoir is unique in that it contains trunion bearings, seals and slip rings which allow the reservoir orientation to remain constant even though it is mounted to a rotating shaft. Use of these components on a hydraulic reservoir was proven by test, and subsequent operating experience has proven this design fully satisfactory. Rotor tip actuators have experienced problems with leaking rod seals. New seals, of improved design and material, have alleviated this problem, and the actuators have subsequently demonstrated a high degree of reliability.

In June 1981 an incident occurred in which the blade tips failed to feather, resulting in an overspeed condition which damaged the generator and quill shaft. Investigation revealed that this was caused by contaminated hydraulic fluid, which caused the start-stop valves to silt up and stick open. As a result, these spool type valves were replaced with poppet type, which are more resistant to silting. Also, position monitors are now being used to warn of any problem with either valve prior to failure of both valves, as only failure of both valves would result in failure of the normal (SSV operated) emergency shutdown system. In addition, an independent emergency shutdown system was added to provide a means of ensuring system shutdown, even in the event of simultaneous start-stop valve failure.

The remainder of the hydraulic system was also re-examined to determine if sufficient redundancy existed in the system to preclude failure. A return line relief valve was identified which, if it stuck shut and electric power was also lost to a solenoid valve, system shutdown would be prevented. A burst disc was added to provide an emergency flow path if the relief valve should stick. However, pressure fluctuations in the hydraulic system would occasionally damage burst discs, and therefore the burst disc was replaced by a relief valve, which will require periodic maintenance testing to verify that neither relief valve has become stuck shut. Also, improved procedures and facilities for monitoring hydraulic oil quality were devised, to preclude component failure as a result of contaminated hydraulic fluid.

5.3.2 Yaw Control System

The yaw control system consists of a hydraulic power unit, a hydraulic motor which drives through a gearbox to turn the nacelle on its yaw bearing so that it faces into the wind, and yaw parking brakes to hold the nacelle in position. These parking brakes are designed to hold the nacelle no yaw rotation occurs in 81 mph winds. The yaw drive subsystem has shown itself capable of rotating the nacelle at the required rate of 1/4° per second. The hydraulic power unit also controls operation of the rotor brake, which restrains rotation of the rotor after shutdown.

Yaw control system problems have been confined to loosening of the yaw drive gearbox fasteners and minor problems with yaw parking brake adjustment. The gearbox fastener problems were solved by adding new fasteners which were installed with an interference fit, and the parking brake adjustment problems were solved by a revised adjustment procedure. It has also proven difficult to control drive pinion clearance as closely as originally desired, but operating experience has shown that increased clearance has no detrimental effect.

A yaw drag brake was originally installed, which was designed to add damping to assure smooth rotation of the yaw bearing. However, some nuisance problems were experienced and operating experience indicated that the yaw bearing has sufficient internal friction to make the additional friction damping of the drag brake unnecessary. When testing confirmed that the drag brake could be removed with no effect on system performance, the design was revised to eliminate this brake function from the wind turbine.

5.3.3 Low Speed Shaft Bearings

The low speed shaft bearings, which support the low speed shaft and rotor, have shown themselves capable of their task, altnough slight problems have been experienced with the bearing lubrication system. Specific problems have been a blocked lubrication passage, seal leaks, and bearing noise. Bearing noise has occurred sporadically during wear in of the bearing, but has not been accompanied by deterioration of bearing surfaces. The blocked lubrication passage was solved by a design change, and seal leakage problem have been nearly eliminated by a revised seal installation and installation procedures.

5.3.4 Low Speed Shaft Slip Ring Bearing

The low speed shaft slip ring transfers electrical signals and power to the rotating equipment on the low speed shaft and rotor blades.. A slip ring bearing seizer on unit #1 resulted in the anti-rotation bracket and LSS wiring being torn loose after less than 300 hours of total operation. The formed wire separator used in the bearing was identified as the cause of the failure. All WTS units subsequently have had the wire separator removed and replaced with a solid brass separator of a circular pocket design. The brass separator has operated satisfactorily on units #1, #2 and #3 for 1300 cumulative hours.

5.3.5 Low Speed Shaft, Quill Shaft, and Coupling

The low speed shaft which supports the rotor and transmits power to the quill shaft, and the quill shaft and coupling which transmit power to the gearbox, have performed well with few problems having been experienced. The June 1981 overspeed incident on unit #1 exposed these components to high overloads, yet the low speed shaft survived with only minor damage to fastener holes which required reaming and oversized fasteners. While the quill shaft underwent considerable yielding, it did not fracture. The quill shaft coupling, which transmits power from the quill shaft via a friction joint, has experienced one incident of slipping. However, this was caused by a failure to clean the coupling friction surface prior to installation, and not by a design deficiency.

5.3.6 Gearbox

The gearbox, which steps up the 17.5 rpm quill shaft speed to 1800 rpm to drive the generator, has proven very trouble free, and capable of high overloads without failure. The overspeed incident which occurred on unit #1 exposed the gearbox to extreme overloads, yet damage to the gearbox was virtually nonexistant. The gearbox has experienced several incidences of oil leakage. Only one of these created any problem, when a defective seal ring hung up and caused a substantial oil leak. All other leaks have been minor nuisance leaks from joints in the gearbox casing, and have been stopped by tightening bolts or application of sealant.

5.3.7 Gearbox Lube System

The gearbox lube system, which is designed to control the temperature of the gearbox lubricant and supply it under pressure to the gearbox, has experienced several problems, including contamination of the lubricating oil with water, and oil pressure fluctuations. The contamination was due to a lack of sealing the oil reservoir and inadequate draining of the nacelle. Addition of drain holes to divert water away from the reservoir has solved this problem. The oil pressure fluctuations, which occur momentarily when the oil cooling radiator control valve cycles, were creating unnecessary system shutdowns. To prevent these shutdowns, as the gearbox is capable of operating with much lower pressures for a short period of time, the lube system pressure switches were readjusted and the delay time altered to decrease the pressure levels which will initiate shutdowns and to increase the time which the system can operate prior to shutdown with only slightly low pressure. Also, the lube system plumbing and control was modified to increase flow and eliminate switch over to the redundant pump during momentary pressure fluctuations. The redundant pump now has become a "ready-spare" by manual switchover.

5.3.8 Generator Bearings

The generator bearings, which are journal type bearings, have had three failures on one of the turbines due to inadequate lubrication. The first failure, caused by a malfunction of the oil heaters which burned the lubricant, was solved by using a different type of generator lubricant and deleting the lubricant heaters. The original lube system design was a passive scoop system delivering oil from the bearing sump. This passive system was found to be inadequate to assure lubrication for the operation at low rpm when the wind turbine was in startup or shutdown or during very slow rotation when positioning the rotor for maintenance.

The subsequent two failures were caused by errors in adjustment of this passive lube feed system while the bearings were being replaced. Therefore, an auxiliary oil feed system to assure oil supply during slow speed and startup conditions has been added. The passive system has been retained, and at high rpm provides adequate lubrication while the machine completes shutdown in the event of loss of the pump power.

5.3.9 Teeter Bearings

The teeter berings, which allow the rotor to tilt slightly to relieve uneven wind loads, have performed within design expectations. No problems have been experienced, and the elastomeric materials appear to be holding up well. The teeter bearing was also exposed to extreme overload conditions during the unit #1 overspeed incident, and survived these overloads with no evidence of damage. The teeter brakes, which were designed to restrain the rotor from teetering when the rotor is rotating slowly, have not performed well. Higher than anticipated loads, and deflections have caused repeated failure of teeter brake mounting bolts. These deflections have also caused excessive wear of the teeter brake slider, and teeter brake pad life has also been shorter than anticipated. Testing with the teeter brakes disabled has shown that the teeter brakes are not required when the rotor is turning, since the rotor has never come close to impacting the teeter stops. Testing has also shown that when the rotor is parked with the teeter brakes disabled, there is an increase in the amplitude of teeter motion to the 6 1/2° travel limit, but no evidence of hard impacts on the teeter bearing stops. This indicates that teeter brake problems have been resolved by elimination of these brakes.

5.3.10 Crack Detection System

The crack detection system, as described in Section 2.2.2 has performed without problem. Its function is to detect a slight difference in air flow between the two blades which would occur in the event of a fatigue crack. Its capability has been demonstrated when a small amount of sealant failed and allowed airflow through a hydraulic line penetration at the spindle area rib at Station 1249.

5.3.11 Manlift

The manlift, which is designed to transport maintenance personnel and equipment up to the nacelle, has worked well and required only minor adjustments to overload safety cutout systems. During the WTS assembly and checkout phase, the manlift has seen more use than it will experience in several years of normal maintenance.

5.4 ELECTRICAL POWER SYSTEM (EPS) PERFORMANCE

5.4.1 EPS Description

The EPS consists of the following major components:

(1) Synchronous Generator - Wind driven (both starting and running) through quill shaft and 17.5 rpm to 1800 rpm gearbox.

(2) Generator Accessory Unit -Cabinet mounted generator circuit breaker and protective relay equipment.

(3) Yaw Slip Ring Assembly - Provides commutation for power and control cabling between nacelle and cable trays along inner tower wall.

(4) Bus Tie Contactor Unit - Enclosed switchgear containing:

   a. Circuit Breaker identical to the circuit breaker in the GAU.
   b. Synchronizing relays
   c. Metering

(5) Generator Stepup Transformer -3125 KVA oil air cooled 12.5 KV grounded Y/4160 volt delta full winding transformer with 2 sets of ±2 1/2% taps and fused manual disconnect switch on high voltage winding. Both HV and LV bushings are enclosed.

5.4.2 Synchronous Generator

Type - Foot mounted, brushless exciter, two disc fed oil lubricated sleeve bearings.

Rating - 3125 KVA, 2500 kW, 1800 RPM, 3 phase, 60 Hertz, 2400/4160 volts, 752/434 amp, 0.8 P.F. at ambient temperatures to 50°C.

Performance - Conservative design of generator is such that machine is capable of producing 3500 kW at unity power factor at a 40°C ambient at altitudes to 3300 feet above sea level. Initial operating experience with the generators has been favorable except for a minor bearing lubrication problem on one machine which was resolved by adjustment of oil scoops. As a result of the investigation associated with the bearing oil problem, it was also determined that:

(1) Oil heaters are not necessary if the proper lubricant is used.

(2) Oil temperature sensors used for the oil heaters were poorly located - e.g., temperature was sensed in an oil cavity which was not directly heated.

(3) Slow roll conditions are present and must be considered when designing the bearing lubrication system.

The following design/procedural changes are being implemented to assure continuing generator bearing lubrication.

(1) Oil heaters have been disconnected.

(2) Lubricant was changed to a flat viscosity lubricant.

(3) A pump lift system to flood bearings with oil during slow roll conditions will be retrofitted on all machines.

5.4.3 WTS Power Protection System

5.4.3.1 Function Description

The WTS Power Protection System contains two identical circuit breakers, one used as the Generator Circuit Breaker (GCB) is located along with protective relaying in the Generator Accessory Unit (GAU). The second circuit breaker is located in the pad mounted metal enclosed switchgear identified as the Bus Tie Contactor Unit (BTCU). The BTCU also contains metering, synchronizing and over/under frequency relays.

The WTS operating scheme is as follows: The GCB is manually closed and opened by protective relays. The bus tie contactor is closed by the Nacelle Control System (NCU) working in conjunction with the synchronizing relays and opened by the NCU working in conjunction with protective relaying.

5.4.3.1.1 Generator Circuit Breaker Operation

The GCB relay (52G) close coil is energized by the application of 48 VDC through the series combination of the GCB close switch (located on GAU front panel) and a normally closed part of GCB tripping relay (86G) contacts.

The GCB relay (52G) trip coil is energized by the application of 48 VDC through a normally open set of GCB tripping relay (86G) contacts. The GCB tripping relay (86G) is energized by any of the following (GAU located) relays:

Reverse Power Relay (32)
Loss of Excitation Relay (40)
Overcurrent Relay with voltage restraint (50/51V
AC Time Overcurrent Relay (51)
Power Factor Relay (55)
Ground Fault Relay (64)
Differential Current Relay (878)

(Number in parenthesis are ANSI device designators)

5.4.3.1.2 Bus Tie Contactor Operation

The bus tie contactor (52BT) closing coil is energized by the application of 48VDC through the series combination of normally open contacts of the following (BTCU located) relays:

Phase Sequence Relay (47)
Synchronizing Relay (25)
Synchronizing Check Relay (25CK)

Synchronizing voltage from the generator requires field excitation which is provided by energizing the field current relay (41) with the field enable signal from the NCU through the series combination of a thermostat and a normally closed set of contacts on the GCB tripping relay (86G).

The synchronizing relay (25) and synchronizing check relay (25CK) are enabled when the sync enable relay (43S) is energized by a sync enable signal from the NCU.

The bus tie contactor (52BT) trip coil is energized by the application of 48 VDC through a pair of normally closed contacts in the bus tie contactor tripping relay (94BT) whenever the NCU energizes the 94 BT relay. The NCU will provide a shutdown signal and energize the bus tie contactor tripping relay (94 BT) when either the under frequency relay (81-1) or the over frequency relay (81-2) apply 48VDC to energize the auxiliary relay (94X) or any one of the three (one for each phase) utility voltage present relays (36V) detect loss of utility voltage. The NCU will also provide a shutdown signal and energize the bus tie contactor tripping relay whenever the generator winding over temperature relay (49G), the generator bearing over temperature relay (38H), the generator bearing under temperature relay (38L) or the AC time overcurrent relay (51) detect out-of-tolerance conditions.

5.4.3.2 Relay Set Points

Reverse Power Relay (32) GE type 12 ICW 51A13A

Tap: 44 watts secondary, 70 KW primary (CT ratio of 80, PT ratio of 20)
Time Dial: 10
Seal in Tap: 2.0 Amps

Loss of Excitation Relay (40) GE Type 12 CEH 51A4A

Seal In Tap: 2
Off-Set: 3 ohms
Restraint: 12%
Input: 99%

Generator Winding Overtemperature Relay (49G) GE Type 12 IRT 53C2A

Seal-In Tap: 0.2 Amps
Time Dial: 2
Temperature Dial: 132°C

Overcurrent Relay with Voltage Constraints (50/51V)

Seal-In Tap: 2.0 amps ___
Time Dial: 5
Tap: 5 amps (200 primary)
Instantaneous Trip: 6.16 ±0.03 amp (493 amps primary)

Time Overcurrent relay (51) GE Type 12IAC51A802A

Seal-In Tap: 0.2 amps
Time Dial: 1
Tap: 5 amps (400A primary)

Power Factor Relay (55) GE Type IC3655A100A

Power Factor Dial: 0.7
Time Delay: 1 sec.

Ground Fault Relay (64) GE Type 12IAV51D2A

Seal-In Tap: 2.0 amps
Time Dial: 1
Coil Tap: 10 volts

Differential Current Relay (87) GE Type 12CFD22A1A

Target: 1 amp
Min. Diff. Current: 0.2 amp

Voltage Present Relay (36V) GE Type 12 HMA 11B11

No set points

Phase Sequence relay (47) GE Type 12ICR51A1A

Time Dial: 2

Over/Under Frequency Relays (81-1, 81-2) GE Type 12 IJF 42A4A

Under Frequency: 59.50 to 59.55 Hz
Over Frequency: 60.45 to 60.50 Hz
Time to Close: 1.0 ±0.1 sec.

Synchronizing Relay (25) Beckwith M-0193A

Upper Voltage Limit: 127.7 ±0.4 VAC (4424V L-L or +6.2%)
Lower Voltage Limit: 114.5 ±0.4 VAC (3966V L=L or -4.6%)
ΔV Limit: 5.0 ±0.5V AC (Multiplier = X1)
ΔF Limit: 0.15 ±0.02 Hz (dial set to 0.015, multiplier = 10)
Breaker Closing time: 120 MS, Jumper between Terminal TB #12 & 20

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Synchronizer Check Relay (25 CK) Beckwith M-0188

Upper Voltage Limit: 127.7 ±0.4 VAC (4424V L-L or +6.2%)
Lower Voltage Limit: 114.5 ±0.4 VAC (3966V L-L or -4.6%)
ΔV Limit: 4 ±0.3 Volt (dial set to 1, represents 140 volt L-L diff)
Phase Angle Limit: 7.5° ± dial set to 5 multiplier = x 1.5)
Time: Dial set CCW stop

5.4.3.3 WTS Power Protection System Performance

Experience to date with the WTS Power Protection System has demonstrated that the system functions very well in detecting fault conditions and preventing damage to electrical equipment. The system also functions well with varying wind conditions and is able to handle power swings with no difficulty. Examination of the protection system design after a year of operation indicates two areas where redundancies exist, the power factor relay and the loss of excitation relay. The loss of excitation relay basically performs the same function; hence, the power factor relay can be disconnected. The functions of the generator circuit breaker and the bus tie contactor can be combined using only one circuit breaker. The logical improved design for future units would be to eliminate the GAU entirely by moving the GAU relays to the BTCU and allowing the bus tie contactor circuit breaker to assume all functions now performed by the generator circuit breaker.

5.4.3.4 Station Service Electrical Protection

The 4160V/460V station service transformer is protected by 40A fuses. Additional station service protection is provided by circuit breakers in the 460V, 208V and 120V panels.

5.4.4 Synchronization System

5.4.4.1 Synchronization System Components

The synchronization system includes the following:

Generator Shaft Speed Control
Synchronizing Relays
Bus Tie Contactor (ciruit breaker)

5.4.4.2 Functional Description

The generator shaft speed is controlled by the rotor pitch control system of the NCU. A control loop compares pulses generated by the shaft encoder with a constant representing the pulse count for synchronous speed (1800 rpm). The speed control system is by design somewhat coarse, since it deals with transients in input torque and the windup/unwind of the soft (quill) coupling shaft.

The NCU rotor pitch control system varies the rotor pitch to accelerate the rotor to a speed of 17.5 rpm. When the rotor reaches 17.5 rpm, the pitch control system varies the pitch to maintain a constant 17.5 rpm rotor speed or a generator shaft speed of 1800 rpm. The NCU issues a synchronizer command which latches a synch enable relay (43S) which enables the synchronizer relay (25) and the synchronizer check relay (25CK). The synchronizer relay (25) will close the bus tie contactor if the generator output terminal and the utility bus voltage and frequency differences are within the set points; provided the synchronizer check relay (25CK) has been enabled. The synchronizer check relay (25CK) looks at the difference between the generator voltage and the utility bus voltage and the phase angle between them. If the voltage and phase differences are within the 25 CK relay setpoints for the time setpoint, the 25 CK relay will provide the contact closure to enable the synchronizer relay (25). The setpoints for the synchronizer relay (25) and the synchronizer check relay (25CK) are listed in Section 5.4.3.

5.4.4.3 Synchronization System Performance

The synchronization system has two open control loops with respect to synchronization. No voltage error feedback signal is sent from synchronizing relays to control generator voltage; and no phase and speed error feedback signal is sent from the synchronizer check relay (25CK) to control generator shaft speed. The generator-voltage regulator and power factor controller are used to control the generator voltage. A closed loop voltage error feedback system would probably synchronize better than the existing system when large swings in system voltage occur. However, the existing system synchronizes satisfactorily with minimal inrush current. The soft (quill) shaft coupling makes the system tolerant to phase errors. Future improvements should include voltage feedback as a minimum and speed feedback control if found desirable by performance analysis.

5.4.5 Slip Rings

5.4.5.1 Yaw Slip Rings

The WTS electrical power system contains a yaw slip ring assembly which contains:

6	High voltage rings - rated 5,000 VAC 650 amps
3	Low power rings - rated 600 VAC 200 amps
4	Low power rings - rated 125 VDC 25 amps
11	Command and control rings - rated 600 VAC 5 amps
101	Signal rings - rated 300 VAC 5 amps

The yaw slip rings are solid 18 inch diameter rings which have functioned well without incident.

5.4.5.2 Rotor Slip Rings

The WTS electrical power system contains a rotor slip ring assembly which contains:

5	Power rings - rated 600 VAC 25 amps
5	Power rings - rated 600 VAC 5 amps
16	Command and control rings - rated 600 VAC 5 amps
50	Signal rings - rated 300 VAC 5 amps

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The rotor slip rings have a diameter of approximately 36 inches. The existing design has a split ring. There have been two problems with the existing design. A wire bearing retainer failed and has been replaced with a punched brass ball separator. All units are being retrofitted with the new separators. The second rotor slip ring problem involves excessive brush wear which has been attributed to the split ring design and the brush material.

Any future MOD-2 WTS will use one piece rotor slip rings with spares of the split ring design to facilitate replacement in the field if necessary. The brush block wear problem is being resolved by replacing all existing (80% silver, 20% carbon) brushes with new brushes made of 75% silver, 20% carbon, and 5% molybdenum disulphide.

5.4.5 Utility Interface

The WTS electrical power system delivers 2.5 MW of three phase, 60 Hz 0.8 to 1.0 power factor, power at 12.5 KV to a utility interface point at fused disconnect switches enclosed in the WTS 4160 volt delta/12.5 KV Y connected power output transformer. Power is transmitted from the utility interface point via direct buried 12.5 KV URD cable to the BPA substation for transformation to 69 KV and wheeling over a 69 KV Klickitat County PUD transmission line to the northwest power grid. The WTS electrical power system is designed and adjusted to operate at unity power factor. It is also designed to operate with low (10% wind turbine generation) penetration. WTS units have operated with isolated loads with good frequency control but could not support the VARS so shutdown occurred. The WTS electrical power system could be modified to enable WTS to operate with isolated loads. The harmonic content of power provided by WTS electrical power system is typical for generating systems employing synchronous machines.

5.5 OPERATIONS AND MAINTENANCE EXPERIENCE

5.5.1 Operations

Unit #1 was first synchronized to the BPA power grid on December 22, 1980. Units 2 and 3 were synchronized on line April 7, 1981, and May 19, 1981 respectively. Since Unit #1 was put into service, the three units have produced over 3,000 megawatt hours during approximately 2,200 hours of operation. The performance summaries of the three units are shown in Table 5-3 and detailed since October 1981 in Tables 5-4 through 5-6. Operating time history is shown in Figure 5-46. Operating time records are shown in Figure 5-3A.

The accumulation of operating time on the machines has been hampered by equipment failures and the need to make modifications and special tests due to the developmental nature of the units. The primary causes of downtime and the resulting changes to the system are discussed in the following sections.

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Table 5-3. Operating Experience 1/1/83 – 10/3/82

	WTS unit			
	No.1	No.2	No.3	Cumulative
Hours of operation	717	1,089	1,288	3,094
Energy generated (kWh)	747,300	1,278,800	1,401,800	3,427,900
Adjusted availability	0.71	0.79	0.83	0.78
Maximum operating winds (mph)	50	50	50	

Table 5-3A. Operating Records (1/1/81 – 10/3/82)

By unit	Longest continuous run	Max operating time between fault shutdowns	Clock time between fault shutdowns
Unit 1	32.3 hours	81.0 hours	289 hours
Unit 2	29.9	45.0	106
Unit 3	36.5	77.0	226
For two units	27.0	50.0	137
For three units	13.0	25.0	47

The primary cause of downtime was the overspeed incident which occurred June 8, 1982 on Unit 1. This incident destroyed the generator and quill shaft on unit #1. Units #2 and #3 were shut down until the cause of the problem was found and corrected. As a result, there was no machine operation from June 8, 1981 to October 20, 1981 when unit #3 was brought back on line. Units #2 and #1 were returned to service November 11, 1981 and April 17, 1982, respectively. To minimize the potential for another overspeed incident, operations of units #2 and #3 were initially restricted to require an operator in the base of the tower whenever the units were operating. This significantly reduced operating time until three shift coverage was provided at the site. In addition, system checks were required at the start of each day which further reduced operating time. The overspeed incident recovery plan calls for the turbines to be phased into completely unattended operation as confidence is gained in the protection systems. As part of this process, the requirement for an operator in each tower has been replaced with a requirement for a person at the site to monitor the data as the machines run, and the frequency of safety system checks has been reduced.

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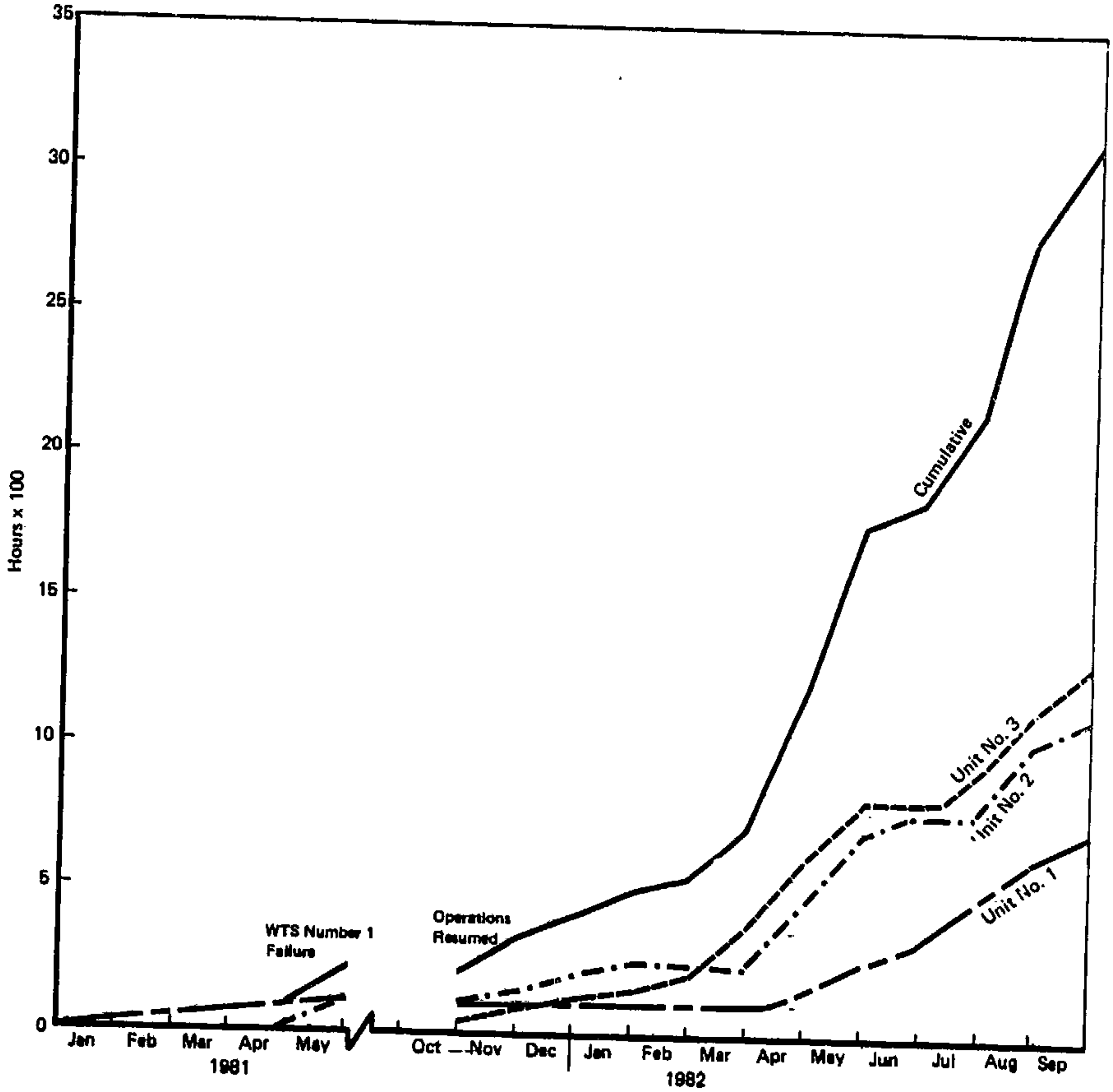

Figure 5-46. Operating Time

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Table 5-4. Performance Summary WTS Number 1

PERIOD	SYNC HRS PERIOD	SYNC HRS YEAR TO DATE	MW HRS PERIOD	MW HRS YEAR TO DATE	AVG MW PERIOD	AVG MW YEAR TO DATE	▷1 PLANT FACTOR PERIOD	▷1 PLANT FACTOR YEAR TO DATE	WTS AVAIL. ▷2 PERIOD	WTS AVAIL. ▷2 YEAR TO DATE	ADJUSTED WTS ▷3 AVAIL. PERIOD	ADJUSTED WTS ▷3 AVAIL. YEAR TO DATE	REMARKS
04/17/82 - 04/23/82	13.4	13.4	16.4	16.4	1.19	1.19	.071	.071	.38	.38	.57	.57	
05/03/82 - 05/09/82	22.3	35.7	21.9	38.3	.98	1.07	.209	.095	.36	.37	.81	.65	
05/10/82 - 05/16/82	48.3	87.2	47.4	84.6	.98	1.02	.192	.132	.85	.54	.94	.78	
05/17/82 - 05/23/82	60.6	147.8	76.8	161.4	1.27	1.09	.210	.159	.84	.65	.97	.86	
05/24/82 - 05/30/82	0	147.8	0	161.4	0	1.09	0	.149	.29	.53	1.00	.87	
05/31/82 - 06/06/82	8.8	156.6	12.3	173.7	1.4	1.11	.27	.156	.16	.49	.93	.87	
06/07/82 - 06/13/82	24.7	181	24.5	198	1.0	1.1	.1	.15	.56	.51	.85	.87	
06/14/82 - 06/20/82	0	181	0	198	0	1.1	0	.13	0	.46	0	.74	
06/21/82 - 06/27/82	0	181	0	198	0	1.1	0	.11	0	.42	0	.65	
06/28/82 - 07/04/82	0	181	0	198	0	1.1	0	.10	0	.40	0	.60	
07/05/82 - 07/11/82	8.1	189	10.0	208	1.2	1.1	.08	.10	.47	.41	.65	.61	
07/12/82 - 07/18/82	53.8	243	71.3	279	1.3	1.1	.23	.12	.83	.45	.88	.65	
07/19/82 - 07/25/82	39.5	283	50.3	333	1.3	1.2	.23	.13	.77	.48	.96	.68	
07/26/82 - 08/01/82	61.2	344	70	400	1.1	1.2	.20	.14	.89	.51	.89	.70	
08/02/82 - 08/08/82	26.6	370	17.2	417	.6	1.1	.07	.13	.78	.53	.82	.71	
08/09/82 - 08/15/82	77.0	447	83.5	500	1.1	1.1	.26	.14	.89	.56	.99	.74	
08/16/82 - 08/22/82	13.7	461	11.8	512	.9	1.1	.04	.14	.50	.56	.97	.75	
08/23/82 - 08/29/82	0	461	0	512	0	1.1	0	.13	0	.52	0	.73	
08/30/82 - 09/05/82	7.9	469	8.8	521	1.1	1.1	.04	.12	.33	.51	.34	.71	
09/06/82 - 09/12/82	11.2	480	10.5	532	.9	1.1	.03	.11	.20	.49	.28	.68	
09/13/82 - 09/19/82	0	480	0	532	0	1.1	0	.11	0	.48	0	.68	
09/20/82 - 09/26/82	4.2	485	5.0	537	1.2	1.1	.11	.11	.17	.47	.74	.68	
09/27/82 - 10/03/82	84.1	569	111.3	648	1.3	1.1	.35	.13	.93	.50	.99	.70	
Total since completion	651		747		1.1		.11		.51		.71		

P = PERIOD TIME

MNT = MAINTENANCE TIME

MOD = MODIFICATION AND PREPARATION FOR SPECIAL TEST TIME

▷1 PLANT FACTOR = $\frac{\text{MWH/PERIOD}}{2.5 \times (\text{P-MOD})}$

▷2 $\frac{\text{P - MOD - MNT}}{\text{P}}$

▷3 $\frac{\text{P - MOD - MNT}}{\text{P - MOD}}$

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Table 5-5. Performance Summary WTS Number 2

PERIOD	SYNC HRS PERIOD	SYNC HRS YEAR TO DATE	MW HRS PERIOD	MW HRS YEAR TO DATE	AVG MW PERIOD	AVG MW YEAR TO DATE	PLANT FACTOR [1] PERIOD	PLANT FACTOR [1] YEAR TO DATE	WTS AVAIL. [2] PERIOD	WTS AVAIL. [2] YEAR TO DATE	ADJUSTED WTS AVAIL. [3] PERIOD	ADJUSTED WTS AVAIL. [3] YEAR TO DATE	REMARKS
11/04/81 - 11/06/81	0	122	0	138	0	1.13	0	.15	.57	.60	1.00	.73	No wind this period
11/09/81 - 11/14/81	9.75	131.75	10.9	148.9	1.12	1.13	.07	.14	.74	.62	.83	.75	
11/15/81 - 11/20/81	6.5	138.25	7.6	156.5	1.17	1.13	.06	.13	.50	.61	.58	.73	
11/21/81 - 11/27/81	.5	138.75	.2	156.7	.40	1.13	.002	.12	.16	.58	.17	.69	3 Day Period Due to Thanksgiving Break.
11/30/81 - 12/04/81	10	148.75	11.1	167.8	1.11	1.13	.097	.12	.47	.57	.62	.68	
12/05/81 - 12/11/81	37.75	187.50	37.2	205.0	.99	1.09	.198	.13	.95	.61	.99	.72	
12/14/81 - 12/18/81	7.0	194.5	10.9	215.9	1.56	1.11	.086	.125	.89	.63	.89	.73	
12/21/81 - 12/25/81	12.0	206.5	16.2	232.1	1.35	1.12	.24	.13	.85	.64	.96	.74	3 Day Period Due to Christmas Break.
12/26/81 - 01/01/82	NO ACTIVITY DUE TO CHRISTMAS BREAK												
01/04/82 - 01/08/82	4.0	4.0	4.0	4.0	1.0	1.0	.076	.076	.24	.24	.48	.48	
01/11/82 - 01/15/82	32.75	36.75	66.6	70.6	2.03	1.92	.658	.459	.79	.53	.90	.76	
01/16/82 - 01/22/82	0	36.75	0	70.6	0	1.92	0	.421	.08	.38	.64	.75	
01/23/82 - 01/29/82	0	36.75	0	70.6	0	1.92	0	.421	0	.28	0	.75	
01/30/82 - 02/05/82	0	36.75	0	70.6	0	1.92	0	.409	0	.22	0	.72	
02/06/82 - 02/12/82	0	36.75	0	70.6	0	1.92	0	.362	0	.17	0	.64	
02/13/82 - 02/19/82	0	36.75	0	70.6	0	1.92	0	.362	0	.19	0	.64	
02/20/82 - 02/26/82	.7	37.45	0	70.6	0	1.88	0	.330	.11	.14	1.00	.67	
02/27/82 - 03/05/82	0	37.45	0	70.6	0	1.88	0	.326	0	.12	0	.66	
03/06/82 - 03/12/82	0	37.45	0	70.6	0	1.88	0	.326	0	.11	0	.66	
03/13/82 - 03/19/82	0	37.45	0	70.6	0	1.88	0	.326	0	.09	0	.66	
03/20/82 - 03/26/82	0	37.45	0	70.6	0	1.88	0	.326	0	.09	0	.66	
03/27/82 - 04/02/82	0	37.45	0	70.6	0	1.88	0	.326	0	.08	0	.66	
04/03/82 - 04/09/82	30.6	68.0	38.2	108.8	1.25	1.6	.182	.254	.49	.15	.89	.78	
04/10/82 - 04/16/82	38.3	106.2	42.0	150.8	1.19	1.46	.207	.238	.52	.20	.71	.76	
04/17/82 - 04/23/82	72.6	178.8	96.2	247.0	1.33	1.40	.241	.239	.76	.28	.80	.77	
04/24/82 - 05/02/82	55.7	234.5	63.3	310.5	1.14	1.32	.163	.219	.67	.33	.80	.78	
05/03/82 - 05/09/82	58.1	292.6	83.2	393.7	1.43	1.35	.256	.228	.42	.34	.79	.78	
05/10/82 - 05/16/82	73.0	365.6	78.5	479.0	1.08	1.29	.214	.225	.76	.38	.89	.80	
05/17/82 - 05/23/82	66.0	431.6	99.5	578.5	1.51	1.34	.258	.233	.64	.41	.70	.78	
05/24/82 - 05/30/82	44.3	475.9	79.0	657.5	1.78	1.38	.367	.244	.73	.42	.90	.79	
05/31/82 - 06/06/82	0	475.9	0	657.5	0	1.38	0	.241	0	.42	0	.79	
06/07/82 - 06/13/82	31.9	508	35.7	693	1.1	1.4	.30	.24	.58	.42	.94	.80	
06/14/82 - 06/20/82	16.7	524	16.9	710	1.0	1.4	.12	.24	.57	.43	.83	.80	
06/21/82 - 06/27/82	11.0	535	8.8	719	.8	1.3	.08	.23	.58	.43	.81	.80	
06/28/82 - 07/04/82	0	535	0	719	0	1.3	0	.23	0	.43	0	.79	
07/05/82 - 07/11/82	0	535	0	719	-	1.3	-	.23	0	.41	-	.79	
07/12/82 - 07/18/82	0	535	0	719	-	1.3	-	.23	0	.40	-	.79	
07/19/82 - 07/25/82	0	535	0	719	-	1.3	-	.23	0	.39	-	.79	
07/26/82 - 08/01/82	0	535	0	719	-	1.3	-	.23	0	.38	-	.79	
08/02/82 - 08/08/82	47.9	583	53.6	772	1.1	1.3	.19	.23	.76	.40	.92	.80	
08/09/82 - 08/15/82	67.8	651	88.7	861	1.3	1.3	.27	.23	.73	.42	.82	.80	
08/16/82 - 08/22/82	22.6	674	15.0	876	.7	1.3	.05	.22	.61	.42	1.00	.81	
08/23/82 - 08/29/82	13.8	688	17.6	894	1.3	1.3	.06	.20	.36	.42	1.00	.82	
08/30/82 - 09/05/82	41.8	729	47.0	941	1.1	1.3	.18	.20	.90	.44	.98	.83	
09/06/82 - 09/12/82	62.8	792	70.4	1011	1.1	1.3	.20	.20	.71	.45	.72	.82	
09/13/82 - 09/19/82	21.6	814	20.6	1032	1.0	1.3	.11	.20	.58	.45	.88	.82	
09/20/82 - 09/26/82	10.0	824	13.4	1045	1.3	1.3	.08	.20	.50	.46	.75	.82	
09/27/82 - 10/03/82	.9	825	1.7	1047	1.9	1.3	.02	.19	.01	.45	.02	.80	
Total since completion	1020		1279		1.3		.18		.48		.79		

P = PERIOD TIME

MNT = MAINTENANCE TIME

MOD = MODIFICATION AND PREPARATION FOR SPECIAL TEST TIME

[1] PLANT FACTOR = $\frac{\text{MWH/PERIOD}}{2.5 \times (\text{P-MOD})}$

[2] $\frac{\text{P - MOD - MNT}}{\text{P}}$

[3] $\frac{\text{P - MOD - MNT}}{\text{P - MOD}}$

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Table 5-6. Performance Summary WTS Number 3

PERIOD	SYNC HRS PERIOD	SYNC HRS YEAR TO DATE	MW HRS PERIOD	MW HRS YEAR TO DATE	AVG MW PERIOD	AVG MW YEAR TO DATE	PLANT FACTOR [1] PERIOD	PLANT FACTOR [1] YEAR TO DATE	WTS AVAIL. [2] PERIOD	WTS AVAIL. [2] YEAR TO DATE	ADJUSTED WTS AVAIL. [3] PERIOD	ADJUSTED WTS AVAIL. [3] YEAR TO DATE	REMARKS
10/26/81 - 10/30/81 Hours = 43	6	24.0	4.9	28.6	.82	1.19	.06	.08	.64	.68	.79	.79	
11/02/81 - 11/06/81 Hours = 42.5	1.5	25.5	1.3	29.9	.87	1.17	.02	.07	.52	.64	.80	.79	
11/09/81 - 11/14/81 Hours = 67.5	10.5	36.0	15.5	45.4	1.48	1.26	.11	.08	.67	.65	.81	.80	
11/15/81 - 11/20/81 Hours = 78.5	22.75	58.75	27.3	72.7	1.20	1.24	.15	.10	.88	.70	.96	.84	
11/21/81 - 11/27/81 Hours = 48	24.5	83.25	22.3	95.0	.91	1.14	.19	.11	.96	.73	1.00	.86	3 day period due to Thanksgiving Break.
11/30/81 - 12/04/81 Hours = 72.5	15.5	98.75	22.4	117.4	1.45	1.19	.19	.12	.27	.66	.41	.81	Actuator Seal Leak
12/05/81 - 12/11/81 Hours = 44	0	98.75	0	117.4	0	1.19	0	.11	0	.61	0	.75	Actuator Seal Leak
12/14/81 - 12/18/81	0	98.75	0	117.4	0	1.19	0	.11	.36	.59	.36	.72	
12/21/81 - 12/25/81	11.75	110.5	12.8	130.2	1.09	1.18	.19	.11	.85	.60	.96	.73	3 day period due to Christmas Break.
12/26/81 - 01/01/82	NO ACTIVITY DUE TO CHRISTMAS BREAK												
01/04/82 - 01/08/82	0	0	0	0	0	0	0	0	.18	.18	.68	.68	Teeter Brake Test
01/11/82 - 01/15/82	0	0	0	0	0	0	0	0	0	.08	0	.22	Teeter Brake Test Servo Valve Change
01/16/82 - 01/22/82	0	0	0	0	0	0	0	0	.48	.23	.63	.44	
01/23/82 - 01/29/82	24.3	24.3	35.1	35.1	1.44	1.44	.23	.111	.55	.34	.66	.55	Corrected YTD Plant Factor 2/9/82
01/30/82 - 02/05/82	11.85	36.15	19.7	54.8	1.66	1.52	.295	.143	.29	.33	.66	.57	
02/06/82 - 02/12/82	0	36.15	0	54.8	0	1.52	0	.132	0	.26	0	.53	
02/13/82 - 02/19/82	0	36.15	0	54.8	0	1.57	0	.117	0	.24	0	.50	
02/20/82 - 02/26/82	3.4	39.55	5.74	60.54	1.69	1.53	.39	.099	.58	.31	.98	.60	
02/27/82 - 03/05/82	38.45	78.0	41.06	101.6	1.07	1.30	.25	.107	.82	.43	.86	.69	
03/06/82 - 03/12/82	44.41	122.41	63.0	164.6	1.42	1.34	.22	.129	.77	.49	.82	.73	
[illegible] - 03/19/82	45.25	168.66	44.1	208.7	.97	1.24	.13	.129	.62	.51	.76	.73	
03/20/82 - 03/26/82	30.90	199.56	44.0	252.7	1.42	1.26	.29	.145	.35	.49	.64	.73	
03/27/82 - 04/02/82	30.20	229.76	36.1	288.8	1.20	1.26	.09	.135	.72	.52	.72	.73	
04/03/82 - 04/09/82	57.90	287.66	61.8	350.6	1.07	1.22	.154	.138	.88	.56	.90	.76	
04/10/82 - 04/16/82	35.30	322.96	29.8	80.41	.84	1.18	.130	.138	.61	.57	.74	.76	
04/[illegible] - 04/23/82	61.1	384.1	73.5	453.9	1.20	1.18	.192	.144	.70	.58	.76	.76	
[illegible] - [illegible]/02/82	56.6	440.7	61.8	515.7	1.09	1.17	.152	.145	.71	.59	.94	.78	
[illegible]	56.9	497.6	75.6	591.3	1.33	1.19	.275	.154	.47	.58	.94	.79	
[illegible]	79.5	570.5	75.9	672.3	1.09	1.18	.198	.158	.82	.60	.92	.80	
[illegible]	[illegible]	620.6	65.5	737.8	1.31	1.19	.188	.162	.65	.61	.78	.80	
05/24/82 - [illegible]	0	620.6	0	737.8	0	1.19	0	.161	.16	.60	1.00	.80	
05/31/82 - 06/06/82	0	620.6	0	737.8	0	1.19	0	.161	0	.58	0	.90	
06/07/82 - 06/13/82	0	620.6	0	737.8	0	1.19	0	.16	0	.57	0	.79	
06/14/82 - 06/20/82	0	620.6	0	737.8	-	1.19	-	.16	0	.55	-	.79	
06/21/82 - 06/27/82	0	620.6	0	737.8	0	1.19	0	.16	0	.54	0	.79	
06/28/82 - 07/04/82	0	620.6	0	737.8	-	1.19	-	.16	0	.53	-	.79	
07/05/82 - 07/11/82	8.5	629	12.2	750	1.4	1.2	.22	.16	.38	.53	1.00	.79	
07/12/82 - 07/18/82	54.7	684	64.6	815	1.2	1.2	.23	.16	.82	.54	.94	.80	
07/19/82 - 07/25/82	26.3	710	29.7	844	1.1	1.2	.13	.16	.87	.55	.96	.81	
07/26/82 - 08/01/82	41.3	751	53.7	898	1.3	1.2	.16	.16	.85	.56	.88	.81	
08/02/82 - 08/08/82	63.5	815	64.0	962	1.0	1.2	.21	.16	.79	.57	.93	.82	
08/09/82 - 08/15/82	77.3	892	91.0	1053	1.2	1.2	.29	.17	.84	.59	.96	.83	
08/16/82 - 08/22/82	22.0	914	12.2	1065	.6	1.2	.04	.16	.62	.59	1.00	.83	
08/23/82 - 08/29/82	12.2	926	16.0	1081	1.3	1.2	.05	.16	.33	.58	.87	.83	
08/30/82 - 09/05/82	28/2	955	26.9	1108	1.0	1.2	.10	.16	.75	.58	.86	.83	
09/06/82 - 09/12/82	54.4	1009	65.9	1174	1.2	1.2	.19	.16	.69	.59	.96	.84	
09/13/82 - 09/19/82	20.9	1030	22.4	1196	1.1	1.2	.09	.16	.88	.59	.91	.84	
09/20/82 - 09/26/82	2.3	1032	.8	1197	.3	1.2	.01	.15	.62	.60	1.00	.84	
09/27/82 - 10/03/82	57.8	1090	74.4	1272	1.3	1.2	.31	.16	.77	.60	.99	.85	
Total since completion	1200		1402		1.2		.15		.60		.83		

P = PERIOD TIME

MNT = MAINTENANCE TIME

MOD = MODIFICATION AND PREPARATION FOR SPECIAL TEST TIME

[1] PLANT FACTOR = $\frac{\text{MWH/PERIOD}}{2.5 \times (\text{P-MOD})}$

[2] $\frac{\text{P - MOD - MNT}}{\text{P}}$

[3] $\frac{\text{P - MOD - MNT}}{\text{P - MOD}}$

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During the overspeed incident investigation, it was found that the life of the bolts in the rotor field joint at Station 360 was considerably shorter than predicted. This necessitated a change in the bolts and the redesign of the joint. Unit #1 rotor field joint was rebuilt prior to being reinstalled after the overspeed incident, and the units #2 and #3 rotors were removed and rebuilt in June and July of 1982. Inspections, changes, and strain gage testing of selected bolts to preclude and correct failures have contributed significantly to system downtime.

Hardware failures are discussed in Section 5.3 and failures since resumption of operations on November 1, 1981 are summarized in Table 5-7. The distribution of failures between the various types of WTS components is shown in Figure 5-47 and their relative contribution to downtime is shown in Figure 5-48. In addition to hardware failure; special tests, logistics problems, and utility outages all contributed to system downtime. Special tests are an ongoing part of the wind energy development program and include accoustical and electromagnetic interference tests. A summary of these tests is presented in Section 3.5.

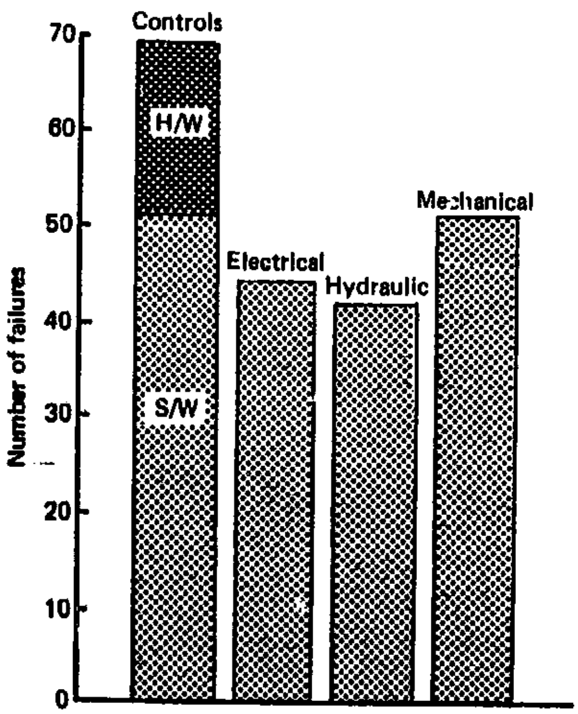

Figure 5-47. Failure Distribution

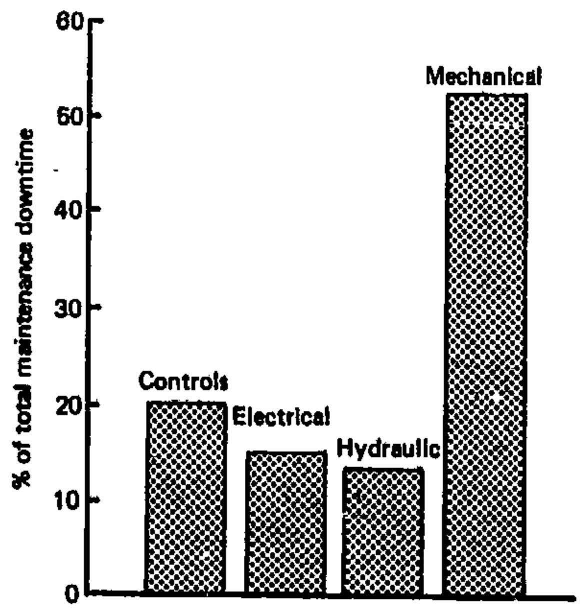

Figure 5-48. Maintenance Downtime Distribution

Table 5-7. Maintenance Experience (Sheet 1)

PROBLEM	UNIT	FAULT CODES/ FAILURE INDICATIONS	ACTION TAKEN
Pressure regulator set too low	3	Gearbox pressure low	Adjusted pressure regulator. Problem appears eliminated
Faulty relay	3	Crack detection motor overload relay tripped	Relay replaced
Yaw programming function and yaw pressure "expected states" not synchronized in software.	3	Yaw oil pressure low	Software change. (DR's F-53, F-49)
Defective fuse (fuse holder that caused the fuse to overheat)	2	Blown fuse A-5 drawer	Replaced fuse. No recurrence in 30 hours operation.
Reservoir slip ring brush block	2	Pitch reservoir low indication	Used spare contactor
Brush block worn (LSS slip ring) due to arcing caused by misalignment	2	Microprocessor getting false states on pitch system pressure	Replaced brush block. Cleaned contacts and rings with isopryl alchol and soft brush.
Actuator gland seal leaking on Blade #1	3	Pitch oil level	Blade 1 & 2, 11 serration Buna-N seals replaced by improved 6 serration Viton seals
Faulty card cage and connectors in A1 card	2	CRT stops updating	Replaced A1 drawer and XA1 card
Incorrect line drivers provided	2,3	CRT fails to update	Replaced A1 card and problem did not recur.
Arcing between adjacent rings due to accumulation of powdered graphite	2	Pitch pump shuts down	Replaced brush block. Modified brush block to minimize graphite buildup. Initiated vendor testing of new brush block materials
Missing wire between ± 15 VDC Power Supply and card cage of A2 drawer	2	Longitudinal vibration indication	Installed missing wire
Faulty A1 card	2	Yaw pump ON/OFF. Transients with system in STBY.	Replaced card
Bolts were not tightened on installation	2	Bolts loose. LSS forward bearing housing	Retorqued bolts
Damaged O-rings on filters	2	Hydraulic oil leak near high pressure filter and at bleed off valves	Replaced O-rings on filters and replaced valves. Valves examined at Boeing. No indication of leakage
Defective anemometer	3	Wind speed anemometer reads half of true speed	Replaced anemometer. Sent to Seattle for investigation (NCR 1420)
Defective A1 card	3	Intermittent HPU	Replaced card
Faulty pump (PSR to be held open until failure report on pump received from vendor	2	HPU pump noise on startup	Rcplaced pump
Poor load distribution paths and insufficient weld callout on drawing	2,3	Aft wind sensor bracket weld area cracked	Braces added to WTS 1,2,&3. Drawing revisions released to fix WTS 5.
Seal configuration and materials inadequate	2	Blade #1 actuator	Replaced with Viton 6 serration seals
A1 card loose in drawer	3	Gearbox pressure low indication	Repositioned connector holding screws to allow deeper seating of card

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Table 5-7. Maintenance Experience (Sheet 2)

PROBLEM	UNIT	FAULT CODES/ FAILURE INDICATIONS	ACTION TAKEN
Temporary wiring installed for special test	2	On-line failsafe tripped	Removed wiring
Unspecified	2	Lube oil radiator leaking	Investigation indicated leakage too minor to require corrective action
Overpressure spike on backside of disc when teeter brake valve opens	2,3	Brust disc ruptures	Burst disc moved from vicinity of teeter brake to reduce sensitivity to teeter brake induced pressure spikes
Miswired sensors	2,3	Vibration indications	Modified SW to instruct MCU to ignore vibration indications when in standby or lockdown unless three indications are given. Corrected wiring associated with sensors.
Incorrect seals on bearings	2,3	LSS bearing seal	Replaced fore and aft LSS bearing seals on WTS 3 and forward bearing seal on WTS 2 with longer seals. Improved installation instructions. Other seals to be replaced as parts become available.
Pressure sag in rotor brake hydraulic circuit during yaw	2	Rotor brake locked indication	SW change causes system to ignore temporary sags when rotor brake release occurs simultaneously with yaw operation
Bolts were probably not torqued on installation	3	Yaw parking brake	Retorqued and subsequently monitored weekly for one month with no indication of further loosening.
Overheated due to close proximity to MCU heaters	2	28 VDC power supply failed	Heat deflectors added to all units by PRR 078
Solder connections on IESS return valve will not sustain loads	2	IESS return valve intermittently causes blade position to wander	PRR 081 will replace with crimped connections
Drag brake housing was not adequately shimmed on installation	2,3	Yaw drag caliper misaligned	Extensive testing has indicated that yaw drag brakes can be eliminated from configuration with no loss of capability
CRT keyboard contact bounce	2	CRT in tower base does not respond to command	Replaced SIO on A5 card
Teeter brake mount bolts failing	2	F205B - Pitch hydraulic pressure low due to sheared hydraulic line. Excessive wear of brake pads observed	Testing underway to determine feasibility of deleting teeter brakes. Interim disposition is to disable teeter brakes and cap hydraulic lines (PRR-092).
Cycling of oil temperature regulator causes drop in pressure		F20B2 - Gearbox oil pressure low indications. Appears to be related to temperature fluctuations requiring bypassing or cycling oil through the cooling loop	Propose to reset pressure switches and time delays to allow the system time to recover from regulator cycling. Propose to change software so that shutdown initiated by the primary pressure switch is a self clearing fault. Testing completed to evaluate above. PRR-097 in progress.
Generator bearings failing prematurely	2,3	F04B2 - Generator bearing temperature high indication. Oil leak at aft generator bearing. Oil discolored.	Generator bearing lube system determined to be inadequate at very low RPM during startup. New lube configuration established and tested by supplier. New lube oil selected. PRR-082 in progress.

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Table 5-7. Maintenance Experience (Sheet 3)

PROBLEM	UNIT	FAULT CODES/ FAILURE INDICATIONS	ACTION TAKEN
Unknown	1,2	F20B5 - Pitch hydraulic pressure low indications near transition to speed control in startup.	Engineering analysis in progress. Instrumentation to be installed to measure blade command.
Excessive wear of slip ring brushes	2,3	Spurious fault indications. Accumulations of silver graphite dust found in slip rings. Shorts caused by arcing of silver graphite dust.	Brush pressure reduced on replacement brushes. New brush material being tested by manufacturer. Monitoring brush block wear every 100 hours. PRR-091 in progress.
Control system over sensitive to gearbox oil level sensor	1,2,3	F80B2 - Gearbox oil level low indication, oil level OK	Control system modified to insert a one second time delay in signal in order to avoid shutdowns for intermittent oil level low indications probably caused by noise in the control system. Testing underway to verify fix.
Control system timing mismatch associated with failsafe tripped indication	2,3	F08B5 - Failsafe tripped. Failsafe is resetable at CRT when it should require a manual reset at the nacelle.	Engineering analysis in progress.
Bearing seals on LSS leaking	2,3	Visual observation	Outside seal on forward bearing modified to include third seal. Monitoring to verify fix.
Unknown	1,2,3	F80B5 - Generator circuit breaker open, no relay flags dropped	Engineering analysis in progress. Possible cause is incorrect setting of relay flag trip points.
Loose connection on power transducer	3	F40B6 - 50% change in power output, but power is steady	Tightened connection.
Power instabilities	1 2	F40B6 - 50% change in power output (power unreasonableness). B80B5 - Generator circuit breaker open. F80B6 - Overspeed indication (also associated with quill shaft coupling slippage). Power oscillations observable on power output data stripout.	Problem is related to operating near the maximum C_p curve at wind speeds close to the rated power transition point. Blade positions on the wrong side of the maximum C_p curve result in power oscillations. Temporary fix is to operate off of the maximum C_p curve at the transition. Software patch implemented (DR-73). Subsequent tests indicate improvement. Engineering analysis in progress on final fix.
SKF coupling slip ring	1	F80B6 - Overspeed indications. Marks on coupling and quill shaft indicate relative motion.	Couping slips when subjected to the the power oscillations described above (WTS 2 coupling does not slip under the same oscillations). WTS 1 restricted to operations in winds below 25 mph. SKF reps to inspect coupling and assist in development of final fix.
Hydraulic oil drains from hydraulic pressure lines when rotor parked vertical	3	F20B5 - Pitch hydraulic pressure low indication prior to breakaway	Normal seepage through the pilot operated check valve and the teeter brake release valve drains the pressure line. During the initial stages of startup the control system detects low pitch pressure before the hydraulic pumps can pressurize the line. Software change to be incorporated which ignores the pitch pressure low indication until the blades achieve breakaway.
Yaw drive bolts loose	2,3	Inspection	Yaw drive bolt torque checked at regular intervals. Engineering analysis in progress for final fix.

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Table 5-7. Maintenance Experience (Sheet 4)

PROBLEM	UNIT	FAULT CODES/ FAILURE INDICATIONS	ACTION TAKEN
Air leaks in rotor	2	F2083 - Blade cracked indication with no detectable cracks	Sealant around the hydraulic line penetration through the station 1248 rib found leaking. Sealant was reworked. Engineering analysis in progress to determine if due to sealant deterioration or initial installation.
Emergency accumulator precharge leaking	1,2,3	F4082 - Pitch emergency accumulator precharge low indication.	Accumulator precharge monitored frequently. Investigation initiated to determine source of leak.
360 joint bolt failures	2,3	Noise in rotor. Broken bolt found.	Bolts changed every 150 hours. 360 joint rework scheduled for units 2 and 3 (PRR-067). Bolt analysis investigation continuing. Unit 1 bolts instrumented to verify joint rework.
Rotor weldment flaws have been detected which are greater than allowable	2,3	X-ray and dye penetrant inspections.	Rework of unit 3 by manufacturer scheduled for 5-28-82. Interim inspection of unit 2 conducted on 4-29. Unit 2 rework scheduled for approximately 7-1.
Gin pole backstay structural failure	1	Structural failure	Backstay redesigned and retrofitted on unit 1. Units 2 and 3 to be scheduled.
Unknown	2	CRT recycles but does not print words on screen	Under investigation
Wiring error in lateral and longitudinal vibration sensors	2,3	Spurious lateral or longitudinal vibration indications	System desensitized to ignore vibration indications for first .3 sec. to avoid shutdown due to noise in system. Longitudinal and latitudinal vibration sensors rewired per drawing correction.
Data problems	3	Instrumentation data stripouts indicate blade not latching. No blade tip differential fault indications.	Data problem. Latch operating normally.
Wheel on operational encoder wearing excessively	3	F4084 - Generator failed to synchronize.	Replaced operational encoder drive wheel with hardened wheel. Changed software to adjust speed control set point to optimize probability of F being in limits with room for wear-in of wheel.
NCU card cage does not grip card securely enough to assure good contact		Spurious fault codes	Spare card cage on order for WTS 3. Card retainers to be incorporated in design.

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Table 5-7. Maintenance Experience (Sheet 5)

PROBLEM	UNIT	FAULT CODES/ FAILURE INDICATIONS	ACTION TAKEN
Prom sockets in A1 cards wear from repeated removals/reinstallations		XA1 card exhibits intermittent operation.	Replacement XA1 cards and extra spares on order.
Burned brush block contacts	3	F20B3 - Blade crack detected - no crack exists.	Changed brush blocks.
Burst discs rupture	2 3	F40B5 - Pitch system fault. F20B5 - Pitch hydraulic pressure low.	Deleting burst disc. Installing 300 psi relief valve (PRR-096).
Defective IESS valve	2	Unable to reach breakaway - F5 fuse in A-5 drawer blown.	Replaced IESS valve. 5-6-82.
Blade does not go to feather	2	F80B4 - Blade tip differential indication	Problem found to be a piece of metal debris which shorted the pitch position potentiometer. Design change in process to add protective enclosure around potentiometer (PRR-094).
Leak in yaw brake area	2	Observation	Problem found to be leaking bleed plugs. Plugs replaced.
Utility power voltage fluctuations greater than expected	2,3	F40B4 - Generator failure to synchronize indication after	Changed synchronizer ΔY to 4 volts.
Failsafe encoder	1,2,3	F20B6 - RPM error indication. Visual inspection of coupling.	Problem found to be encoder alignment. Couplings removed and replaced and encoders realigned.
Defective chip in the XA1 card	3	Subsystem startups occur during NCU power-up sequence. Loss of manual control.	[illegible]moved and replaced chip #3 on the [illegible]1 card.

Spare parts shortages were the primary logistics problem. While spare parts were generally available in Seattle, when parts were needed at the site, a day was the minimum response time achievable. In March 1982, facilities for spares storage were obtained at the site. This greatly reduced the downtime associated with lack of spares. In addition, there were failures where spares were not in the warehouse because they had never been ordered or had been used and a replacement had not arrived. One example of this was the actuator seal replacement on unit #3 which required a weeks downtime while the actual task of seal replacement took two days. The spare actuator seals had been used on unit #1 and replacements had not arrived when needed.

Utility outages also contributed to system downtime. While most outages were attributed to faults on the utility grid and/or scheduled maintenance of the line, several outages were caused by problems at the on-site substation. One of these resulted from a ground squirrel working its way into the connection vault in the substation and causing a fault. A change to the design of the vault resolved this problem.

While there have been a considerable number of problems, much of the downtime has been associated with recurring problems for which fixes were not yet implemented. Over 70% of the downtime results from recurring problems. As the causes of these failures are found and resolved, the performance of the machines is steadily improving. This is discussed further in Section 5.5.3.

5.5.2 Maintenance

5.5.2.1 Maintenance Experience

The maintenance actions accomplished at the site have ranged from major repairs of unit #1, (after the overspeed incident) to the sampling of hydraulic fluid as part of a scheduled two-month maintenance action. All required activities have been completed with no major problems encountered due to the elevated location of the nacelle or lack of adequate space for maintenance or repair. Transportation of tools and parts to the nacelle is easily accomplished by use of the tower manlift or a pulley and bucket system rigged in the tower. In addition, transportation of large or heavy items to and from the ground has been accomplished using the monorail mounted hoist through the aft nacelle door.

The time required for maintenance tasks has generally been close to the estimated value. For example, changing an actuator seal required approximately 16 hours and three men. The predicted requirement for this task was 16 hours and two men. While experience shows that three men will always be required for safe completion of this task, as a crew becomes experienced in the rigging and operation of the rotor access device it is expected that the time required for the task will be 10 to 12 hours.

A typical example of a less major maintenance activity was replacement of an "O" ring in the yaw hydraulic system valve manifold. A similar activity was predicted to require 9 manhours for a mature system with experienced maintenance crew. The task actually required 13.5 manhours the first time it was done. Again, it is reasonable to believe that the mature system prediction is achievable as experience is gained by the crews.

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One area where significantly more manhours are required than the prediction is in scheduled maintenance. The present documented requirements for scheduled maintenance are 270 manhours while the original maintenance analysis of mature production in large farms predicted 72 manhours. The tasks required are shown in Table 5-8. It is expected that as confidence is gained in the WTS subsystems the frequency of many of the scheduled actions will be reduced. In addition, as the design is matured, subsystems requiring excessive scheduled maintenance can be modified to reduce this requirement. The impact of this increased scheduled maintenance on system power output is not as significant as an equal amount of unscheduled downtime because a large percentage of the scheduled maintenance action can be completed during low wind periods. Experience at Goldendale has shown that activities can be scheduled around wind availability relatively easily.

Data gathered during the disassembly of unit #1 following the overspeed further supports the accuracy of maintenance requirement estimates. A comparison of the estimated and actual times required for various tasks is shown in Figure 5-8A.

	Maintenance manhours		Time to complete (hours)	
	Analysis estimate	Actual experience	Analysis estimate	Actual experience
Prep for rotor removal	48	60/64	16	16/16
Rotor removal	56	88/88	8	8/8
Prep for nacelle removal	48	30	16	8
Nacelle removal	72	80	8	8
Teeter bearing removal	48	60	8	24
Tip separation from mid	64	40	16	8
Actuator seal change	32	48	16	16
HPU "O" ring change	9	14	6	7
Two month scheduled	19	24/32	10	11/13
Six month scheduled	32	78/84	20	22/36

Figure 5-49. Maintenance Time Comparisons

5.5.2.2 Special Maintenance Tools

The special tools developed for MOD-2 maintenance are shown in Figure 5-50. Most of the tools specially designed for use on the wind turbine have been utilized as part of the WTS maintenance. This equipment has functioned well, particularly the rotor access device and drive train position and lock tools which have been used frequently. The rotor access device has been used for changing the actuator seals, inspecting the tip area hydraulics, and inspecting the crack detection sealant. It

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Table 5-8 Scheduled Maintenance Requirements Summary

Functional area	Maintenance task	2 mo	6 mo.	12 mo	24 mo	5 yr.	10 yr.	Procedure reference [1]
Rotor	Structural/crack inspection (1st year only)	X						5.2.2.17
	Structural/crack inspection (2nd year only)		X					5.3.2.23
	Structural/crack Inspection			X				5.4.2.1
	Inspect seals and lubricate spindle bearings			X				5.4.2.1
	Inspect tip hydraulics			X				5.4.2.1
	Inspect tip swivel actuator and lock mechanism			X				5.4.2.1
	Clean and repaint tip blade					X		5.6.2.3
	Clean and repaint entire rotor						X	5.7.1.1
Teeter	Inspect teeter stops	X		X				5.2.2.1/5.4.2.2
	Inspect teeter bearings			X				5.2.2.2
L.S.S.	Inspect and test LSS mounted pitch hydraulics	X						5.2.2.2
	Sample and analyze hydraulic oil	X						5.2.2.2
	Test pitch hydraulic pressure and temperature switches				X			5.5.2.1/.2
	Inspect/service crack detection system	X		X				5.2.2.3/5.4.2.5
	Inspect and service LSS bearing assemblies	X						5.2.2.4
	Change bearing lube oil			X				5.4.2.6
	Test bearing temperature sensors				X			5.5.2.1
	Inspect and service RPM sensor installations	X						5.2.2.5
	Inspect and service slip ring assemblies	X	X					5.2.2.6/5.3.2.6
	Inspect quill shaft coupling	X						5.2.2.7
Gearbox	Inspect/service gearbox dehumidifier	X			X			5.2.2.8/5.5.2.2
	Test and service gearbox lube system	X						5.2.2.9
	Gearbox visual inspection		X					5.3.2.9
	Gearbox lube oil analysis		X					5.3.2.10
	Gearbox major inspection					X		5.6.2.1
	Test critical pressure and temp. switches				X			5.5.2.1/.2
H.S.S	Inspect high speed shaft coupling	X						5.2.2.10
	Inspect rotor brake	X						5.2.2.12
Generator	Check generator lube oil level	X						5.2.2.11
	Test insulation resistance		X					5.3.2.12
	Change generator lube oil, inspect/clean winding and exciter, check bearing wear			X				5.4.2.13
	Test critical overtemp switches				X			5.5 2.1
GAU	Inspect ground fault and diff protection relays		X					5.3.2.13
	Inspect and service GCB, overcurrent relay, tripping relay and voltage regulator			X				5.4.2.14
	Inspect and service loss of excitation relay, reverse power relay, time O.C. relay,- and auxiliary relays				X			5.5.2.4
Yaw	Inspect yaw brake mechanisms	X						5.2.2.12
	Inspect and service yaw/rotor brake hydraulic system	X						5.2.2.12
	Change yaw hydraulic oil supply filter		X					5.3 2.14
	Functional test yaw hydraulics overtemp, oil pressure switches				X			5.5.2.1/.2
	Inspect/service yaw slip rings			X				5.4.2.15
	Inspect yaw drive gear reducer	X						5.2.2.12
	Lubricate yaw ring gear pinion and bearing	X						5.2.2.12
	Change yaw-drive gearbox lube oil			X				5.4.2.15
	Inspect yaw bearing support structure and gear reducer fasteners		X					5.3.2.14
NCU	Recalibrate power supplies		X					5.3.2.15
	Test fail safe system	X						5.2.2.13
Nacelle General	Inspect/service fire protection system	X	X	X		X		5.2.2.14/5.3.2.10 5.4.2.17/5.6.2.2
	Inspect and test ventilation system		X					5.3.2.16
	Check operation of A/C warning lights	X						5.2.2.14
	Nacelle general/structural inspection			X				5.4.2.17
	Inspect Nacelle safety equipment		X					5.3.2.16
	Recondition rescumatic units					X		5.6.2.2
Tower	Inspect and service manlift	X	X	X				5.2.2.16/5.3.2.18 5.4.2.19
	Inspect and test uninterruptable power system	X						5.2.2.15
	Tower general/structural inspection			X				5.4.2.20
BTCU	Insp ct and test phase sequence relay		X					5.3.2.19
	Inspect and service bus tie breaker freq. relays, aux. relays, KVAR/KWH meters, and disconnect switch			X				5.4.2.21
	Calibrate meters					X		5.6.2 4.
XFMR	Inspect and service output transformer		X					5.3.2.20
WTS General	Pitch control response test		X					5.3.2.21
	Inspect WTS elect. bonding connections			X				5.4.2.24
	Inspect safety equipment			X				5.4.2.25
	WTS general cleaning/repainting						X	5.7.1

[1] See Reference 4

- Rotor lock assembly
- Rotor positioner
- Teeter positioner and lock assembly
- Rotor access device (Spider staging)
- Rotor tip positioner and lock assembly
- Rotor tip removal set
- Gearbox tool set
- SKF coupling tool set
- NCU field test unit (FTU)
- Hydraulic oil sampling kit

Figure 5-50. Mod-2 Unique Maintenance Equipment

functions extremely well, requiring three men approximately four hours to rig and has been used successfully in winds up to 30 mph; however, maintenance crews feel that 20-25 mph is the maximum comfortable working wind speed. The drive train position and lock tools and the rotor access device are shown in use in Figures 5-51 and 5-52 respectively. Other tools and test equipment required for maintenance are shown in Table 5-9.

The gearbox maintenance tools were used to disassemble unit #1 gearbox following the overspeed incident. They worked very well, with a complete disassembly inspection and reassemby of the gearbox accomplished in less than a week.

The rotor position and lock tools are used frequently to position and secure the drive train for maintenance. The original plan was to have one set of this equipment for each WTS cluster. It is now felt that considering the frequency with which they are used, this equipment should become an integral part of each WTS.

5.5.2.3 Maintenance Manuals and Training

A MOD-2 Operations and Maintenance Instruction Manual (Reference 4) has been prepared and is in use for maintenance at the site. The manual contains a system description as well as sections on scheduled maintenance, troubleshooting, changing components, maintenance tool requirements, system operations, and component adjustment and test. Data supplied by the vendor for approximately 50 major subassemblies and components are included as appendices to the basic manual. The manual was first issued in December of 1980 and has since been updated to reflect changes in system configuration, and to incorporate changes resulting from field use.

The manual was used as a training aid in the operations and maintenance training course conducted for Bonneville Power Administration personnel. This four-week course consisted of both classroom and field work. Topics covered included: principles of WTS operation and design, a detailed description of all wind turbine systems, proper use of all unique maintenance equipment, safety aspects of operation and maintenance, troubleshooting, and scheduled maintenance requirements. Emphasis was placed on safe operations and maintenance of the machines, and personnel were qualified in the use of the "rescumatic" emergency escape device by a short training jump. BPA personnel who will be primarily responsible for maintenance of the systems have been assisting Boeing crews in the maintenance of the units, thus supplementing the formal training class.

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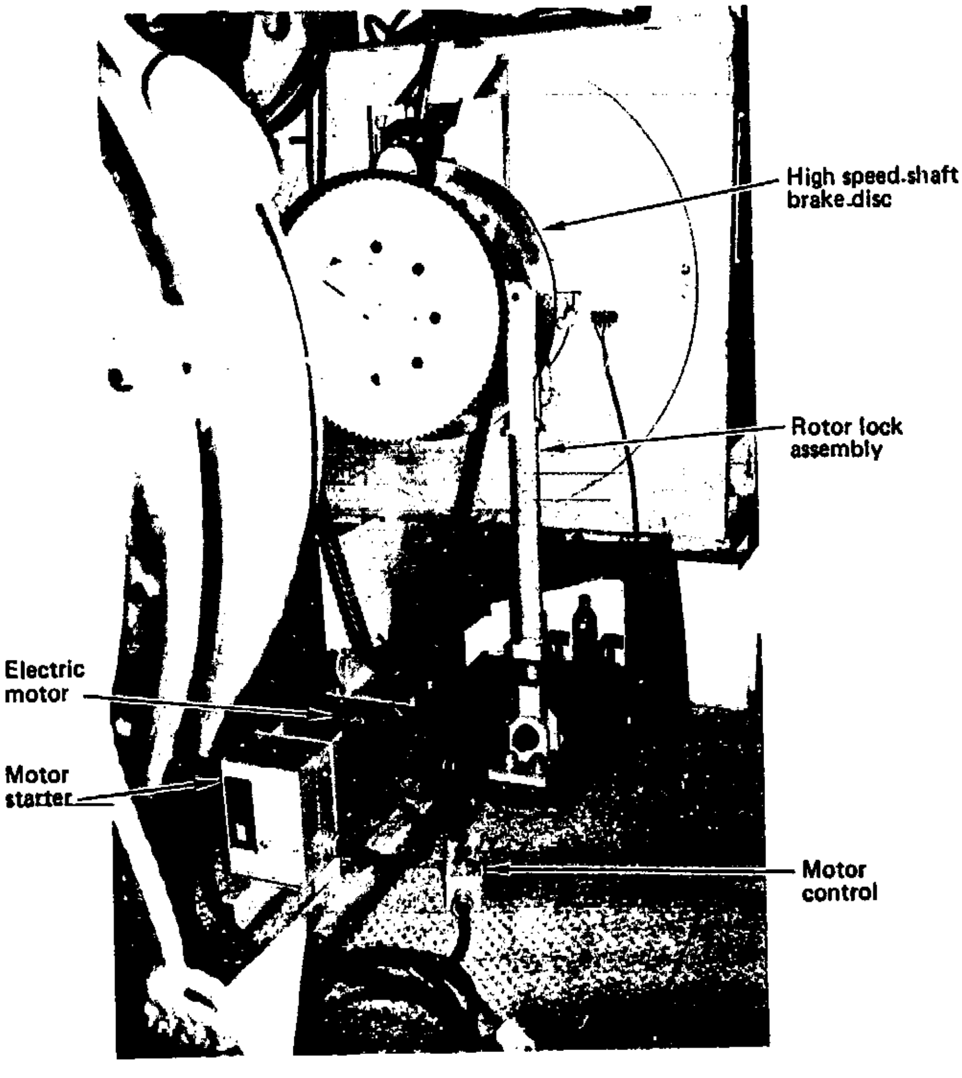

Figure 5-51. Rotor Positioner and Lock Installation

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Figure 5-52. Rotor Access Device Installation

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Table 5-9 Special Support Equipment

Ref. no.	Name	Part no.	Source	Paragraph reference [1]	Use
R-1	Rotor lock assembly	032-490005-1	Boeing	8.1.1	Positive lock of rotor/drive train during maintenance
R-2	Rotor positioner	032-490004-1	Boeing	8.1.1	To manually rotate and position rotor/drive train
R-3	Teeter positioner and lock	032-490002-1	Boeing	8.1.2	Manually position and secure rotor in teeter axis
R-4	Rotor tip positioner and lock	032-490009-1	Boeing	8.1.3	Manually position and secure blade tip
R-5	Rotor tip removal set	032-490003-1	Boeing	8.1.4	Blade tip replacement
R-6	Hoisting and handling equip.	See Appendix A-45	Boeing (Beebe)	8.1.5	Component removal and installation
R-7	Rotor access device	032-490001-1	Boeing (Spider)	8.1.6	Inspection/maintenance of rotor assembly
R-8	Gin pole	See Appendix A-44	Boeing (N.S.E.)	8.1.12	Rotor removal and installation
G-1	Gearbox tool set	See Appendix A-23	Boeing (Stal-Laval)	8.1.8	Gearbox repair
G-2	SKF coupling tool set	See Appendix A-21	Boeing	8.1.8	Attach/detach LSS aft coupling
C-1	NCU field test unit	032-490010-1	Boeing	8.1.9	Test and troubleshoot NCU microprocessor assembly
M-1	Oil sampling kit	032-490011-1	Boeing	8.1.7	Draw pitch hydraulic oil sample
M-2	Portable air compressor		Available locally	8.1.11	Provide compressed air source
M-3	Hydraulic service kit		Available locally	8.1.11	Drain, purge and refill pitch or yaw hydraulic systems
M-4	Nitrogen charging kit		Available locally	8.1.11	Recharging hydraulic accumulators
M-5	Portable ventilator		Available locally	8.1.11	Provide ventilation while working inside rotor
M-6	Lube support kit		Available locally	8.1.11	Servicing lube oil in gearbox, LSS bearings and generator
M-7	Relay/breaker maintenance equip.		Purchase locally	8.1.11	Servicing GE relays and breaker carts
M-8	Maintenance equip. set, electrical		Available locally	8.1.11	Troubleshooting and repair of electrical/control systems
M-9	General purpose tool set		Available locally	—	General maintenance
M-10	Convenience equip. (ladders, portable lights, portable heater, etc.)		Available locally	—	General use during maintenance
M-13	Transit	—	Available locally	—	Aligning wind sensor to nacelle heading
M-14	Servo analyzer	Model SA-2	ACS hydraulics	8.1.11	Testing pitch servo valve
M-15	Optical tachometer		Available locally	—	Troubleshooting RPM encoder systems
M-16	Dial indicator		Available locally	—	General use in maintenance

[1] See reference 4.

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5.5.3 Availability

Availability of the MOD-2 units has been tracked to assist in evaluating machine performance. Two methods of computing availabity have been used. The first presents the percentage of the time the turbine could have operated if wind and crews were available. It is computed using the equation:

$$A = \frac{\text{Period time - Downtime}}{\text{Period Time}}$$ where

Period time is all time that operators were available to monitor the machines and downtime is any time the machines were not capable of operating during the period. There are three categories of downtime: These are maintenance, modifications and special tests.

The second method of computing availability, known as adjusted availability, attempts to determine what the availability of the machines would be if no modifications or special tests associated with the development of the machines were being conducted. The equation used for this calculation is:

$$A = \frac{\text{Period - (Downtime)}}{\text{Period - Modification time - Special Test Time}}$$

This "adjusted availability" more closely represents the capability of the MOD-2 WTS after the initial checkout and test period in which hardware and software modifications are correcting initial design deficiencies. Adjusted availability also eliminates from period time, all downtime for special tests such as evaluation of noise, TVI, and wake effects.

Typical examples of modification and special test time are shown in Figure 5.53.

Rotor 360 joint changes
LSS bearing seal modifications
Gear box modifications
Generator bearing modifications
Control system improvements
LSS noise investigation
Slip ring inspection and test
Yaw drag brake test
Teeter stop bumper test
IESS harness modification
Brush block modification
Servo valve harness modification
Special tests

Figure 5-53. Typical Modifications

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Period time in both of these equations represents only the time crews were available at the site since the machines have not yet been cleared for completely unattended operation. In addition, period time does not include time the machines were down for modifications following the overspeed incident.

The cumulative availability history trends are shown in Figure 5-54 through 5-57, and monthly average availabilities are shown in Figure 5-58 through 5-61. These data are also provided in Tables 5-10 and 5-11.

The discontinuity on these charts between the end of May 1981 and October 1981 is the period all three turbines were shutdown as a result of the overspeed incident. The dip in the four week availability of unit #2 (Figure 5-55) during January and February is the result of the rotor Sta. 360 modifications. The zero availability recorded during March is the result of the generator bearing modification. The affect of this period on the adjusted and unadjusted cumulative availabilities can be seen in Figure 5-55. While the unadjusted availability has a dip in this period, the adjusted cumulative availability is not affected by the modification downtime.

The availability of unit #3 was low during late 1981 and early 1982 for a variety of reasons. In December, the pitch actuator seals were changed on both tips, and in January the rotor access device was used to change a servo valve. In addition, a tip mounted IESS valve installed as a result of the overspeed incident developed a poor electrical connection which was repaired. These items were treated as maintenance time and resulted in decreases in both basic and adjusted availability. In March, basic availability remained low as a result of rotor Sta. 360 joint modifications.

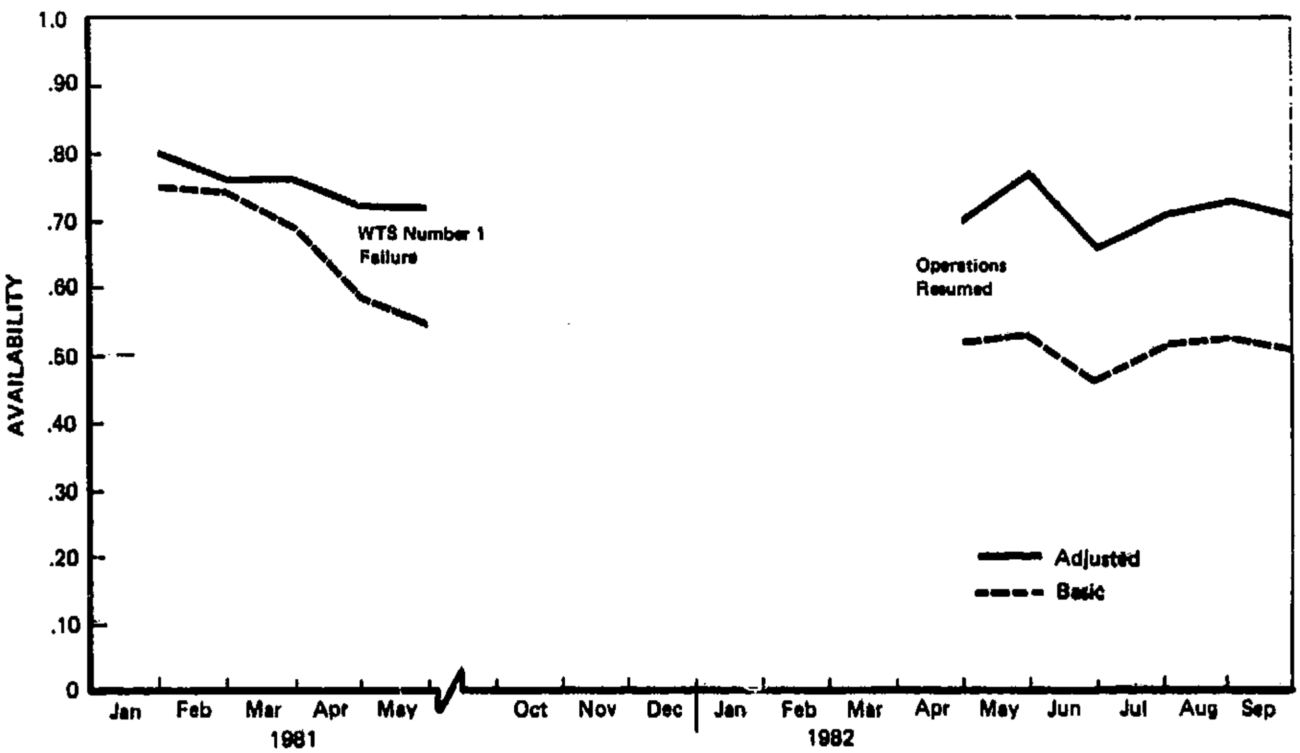

Figure 5-54. WTS Number 1 Cumulative Availability

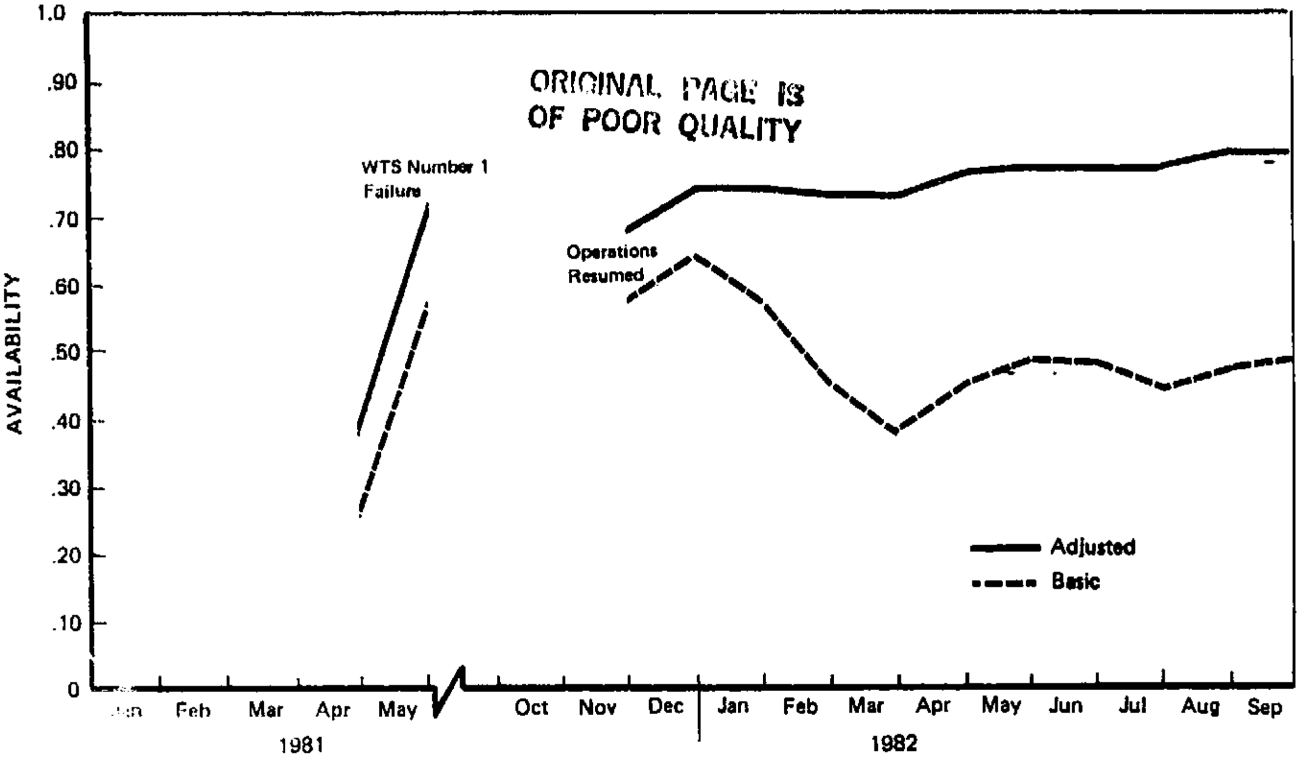

Figure 5-55. WTS Number 2 Cumulative Availability

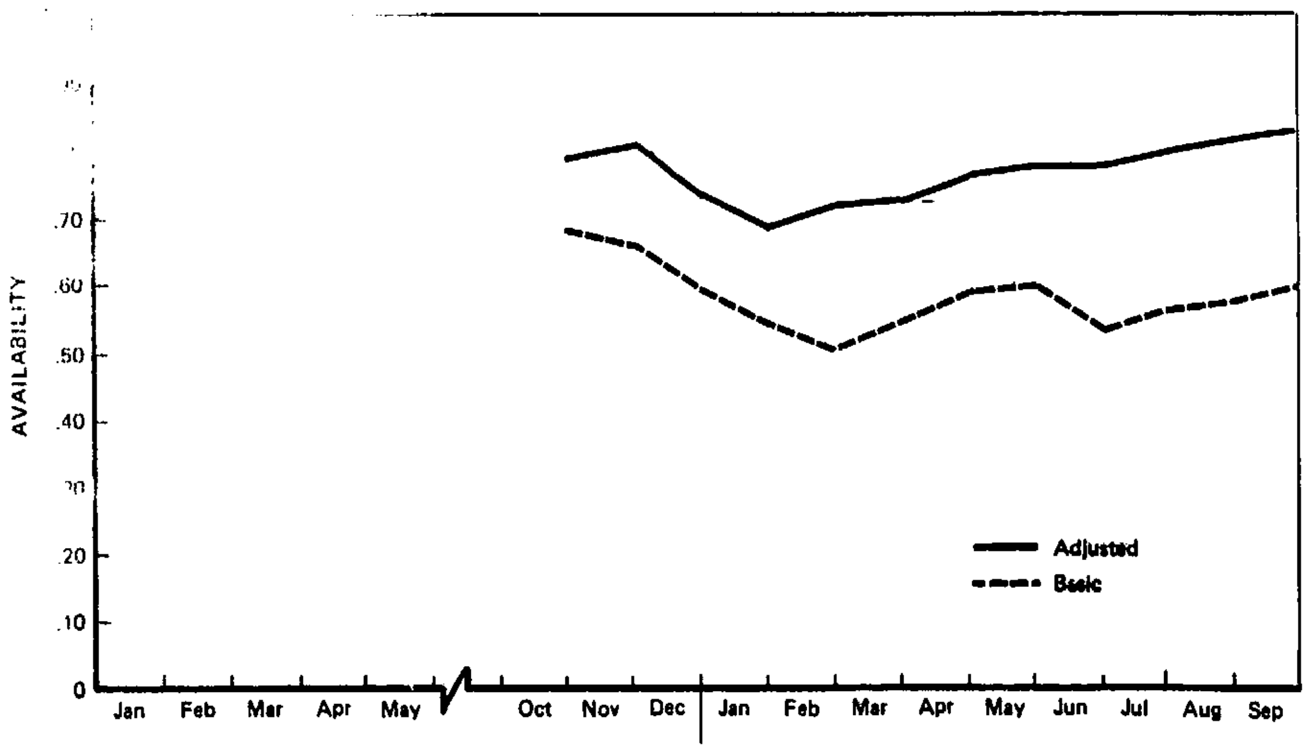

Figure 5-56. WTS Number 3 Cumulative Availability

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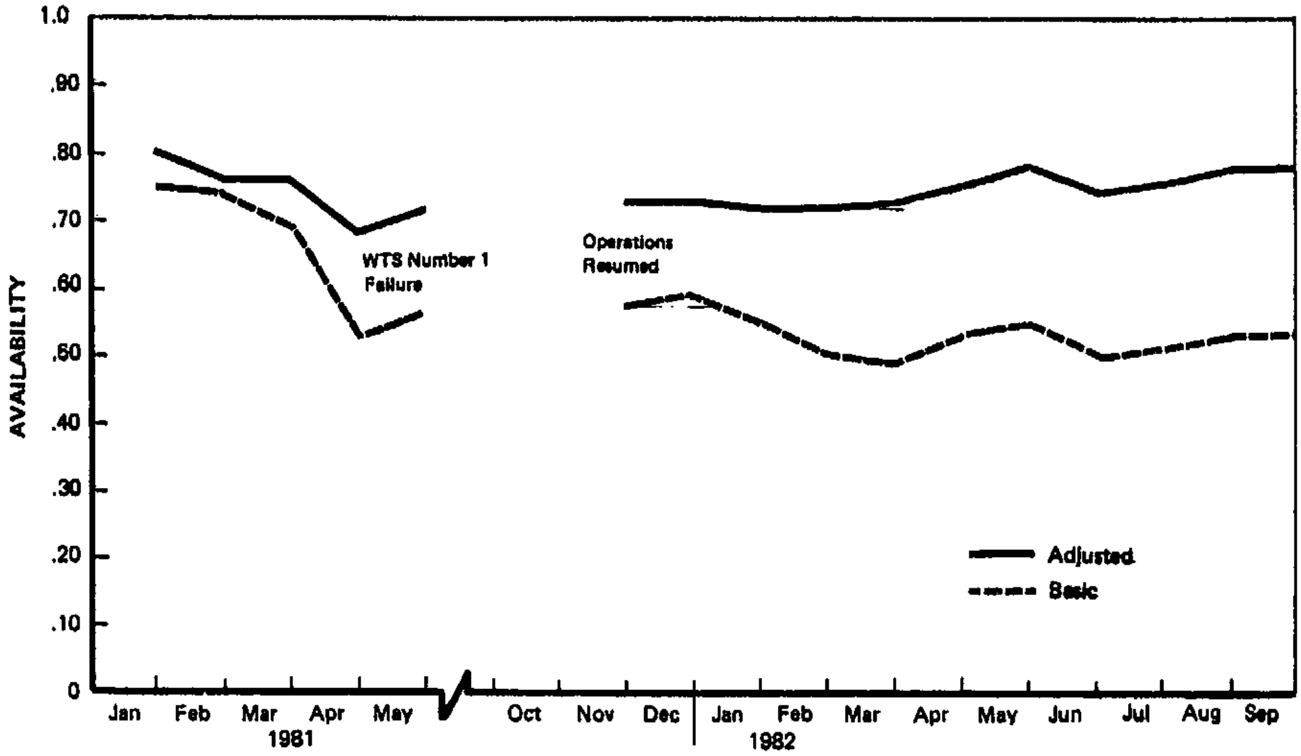

Figure 5-57. Cumulative Availability All Three Units

Table 5-10. Cumulative Availability

	Unit no. 1		Unit no. 2		Unit no. 3		All units	
	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted
January 1981	.75	.80	–	–	–	–	.75	.80
February 1981	.74	.76	–	–	–	–	.74	.76
March 1981	.69	.76	–	–	–	–	.69	.76
April 1981	.58	.72	.26	.40	–	–	.53	.68
May 1981	.54	.72	.60	.72	.71	.80	.57	.72
November 1981	–	–	.57	.68	.66	.81	.58	.73
December 1981	–	–	.64	.74	.60	.73	.59	.73
January 1982	–	–	.57	.74	.54	.69	.55	.72
February 1982	–	–	.45	.73	.51	.72	.50	.72
March 1982	–	–	.38	.73	.56	.73	.49	.73
April 1982	.52	.70	.45	.76	.59	.77	.53	.75
May 1982	.53	.77	.49	.77	.60	.78	.54	.78
June 1982	.47	.66	.48	.77	.54	.78	.50	.75
July 1982	.52	.71	.44	.77	.57	.80	.51	.76
August 1982	.53	.73	.47	.79	.58	.82	.53	.78
September 1982	.51	.71	.48	.79	.60	.83	.53	.78

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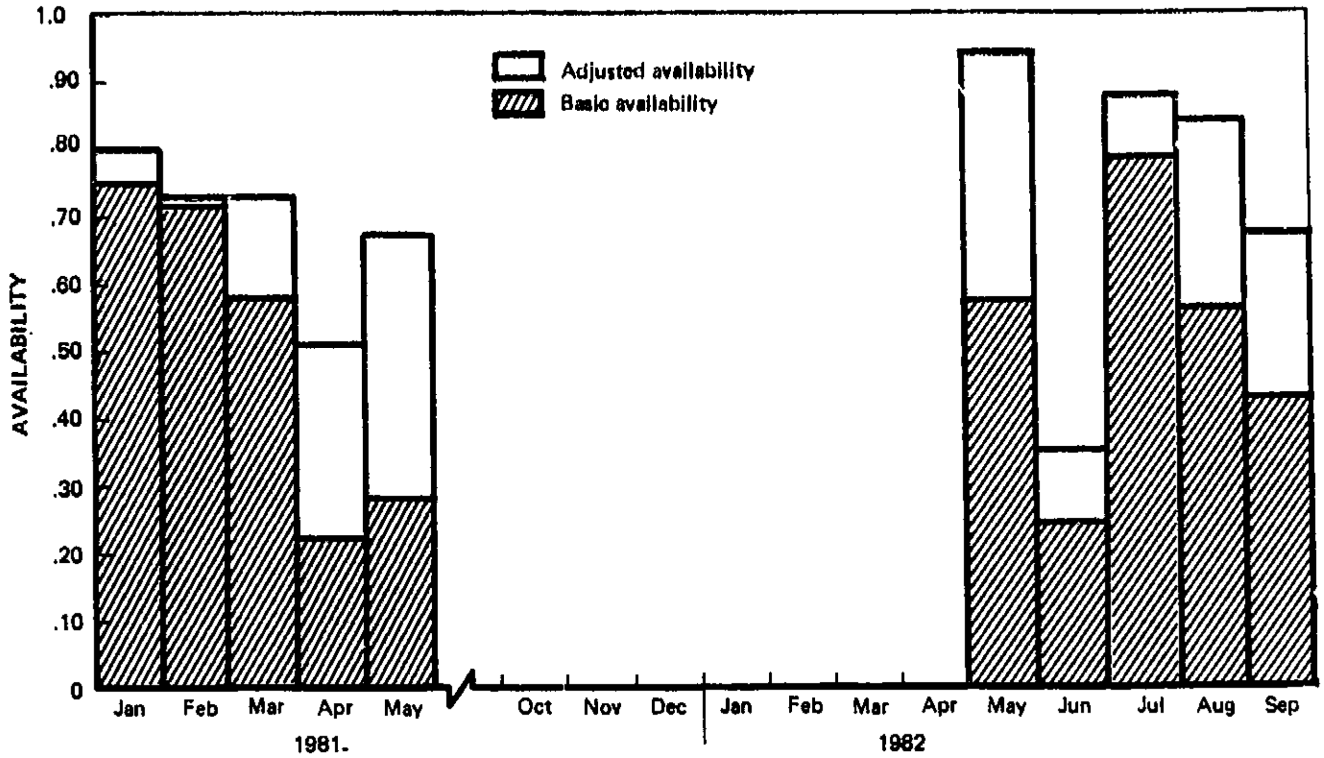

Figure 5-58. WTS Number 1 Availability Four Week Average

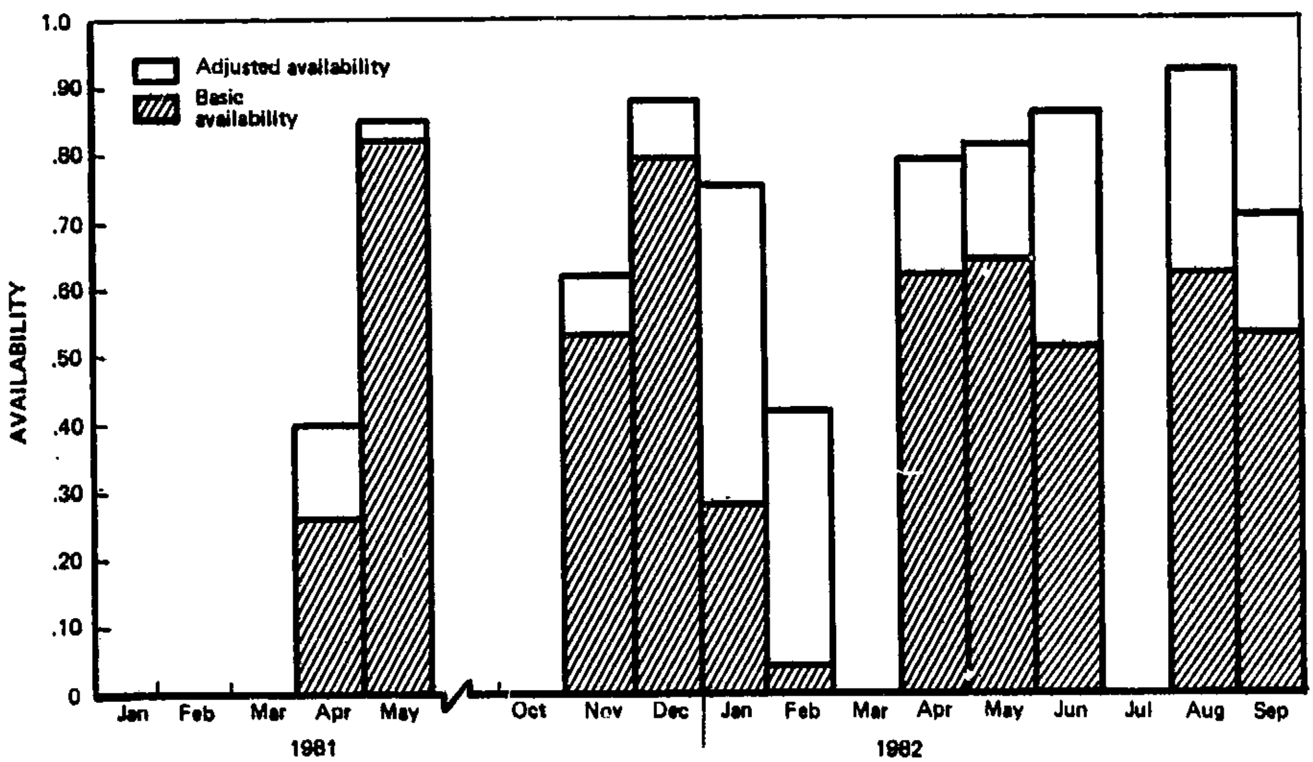

Figure 5-59. WTS Number 2 Availability Four Week Average

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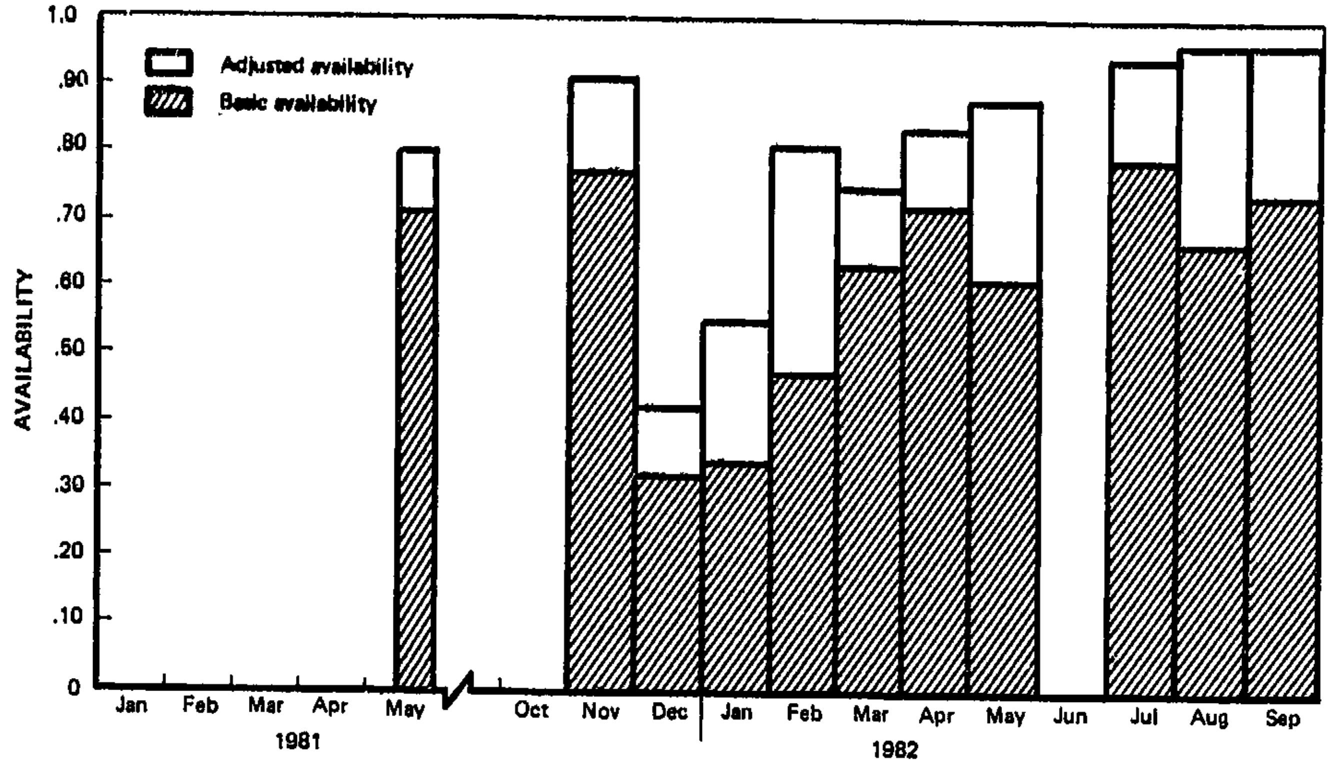

Figure 5-60. WTS Number 3 Availability Four Week Average

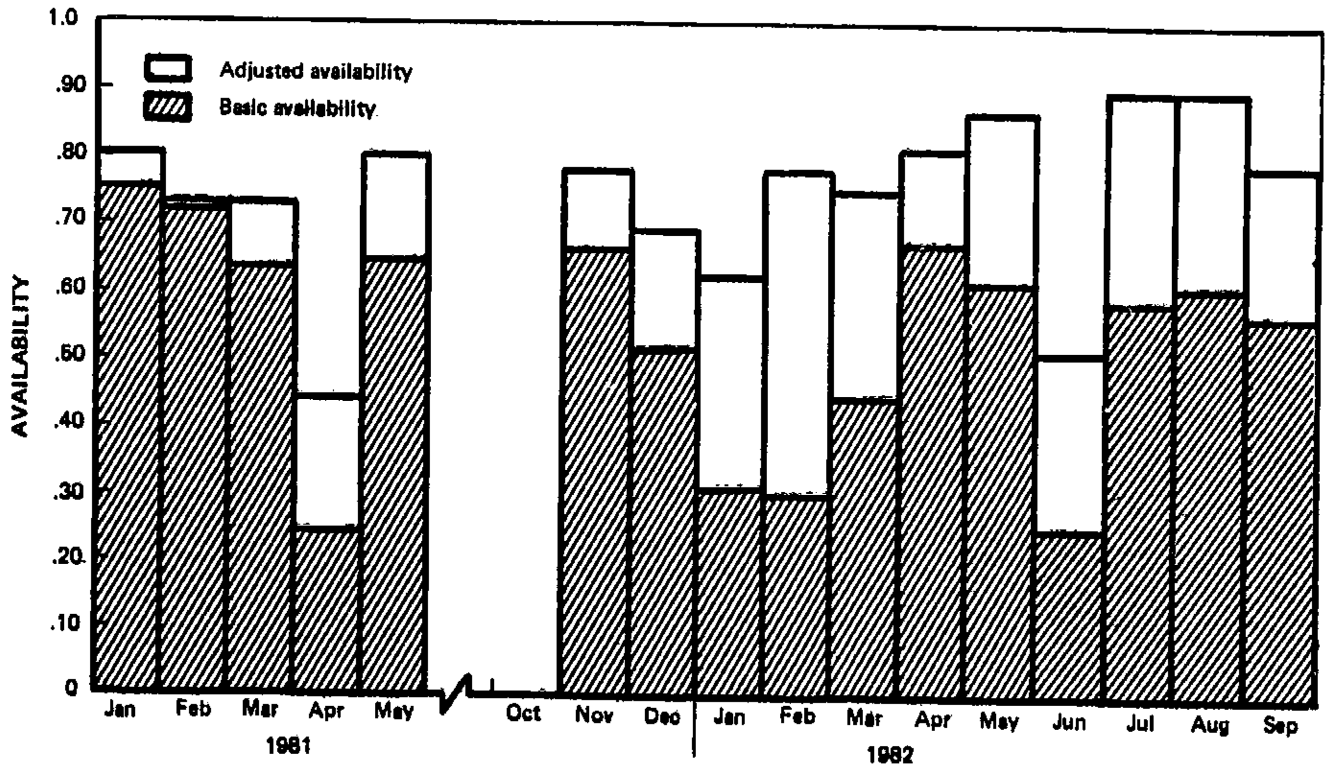

Figure 5-61. Four Week Average All Operating Units

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Table 5-11. Monthly Availability

	Unit no. 1		Unit no. 2		Unit no. 3		All units	
	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted	Basic	Adjusted
January 1981	.76	.80	–	–	–	–	.76	.80
February 1981	.72	.73	–	–	–	–	.72	.73
March 1981	.58	.73	–	–	–	–	.63	.73
April 1981	.22	.51	.26	.40	–	–	.24	.44
May 1981	.28	.67	.82	.86	.71	.80	.64	.80
November 1981	–	–	.53	.62	.77	.91	.66	.78
December 1981	–	–	.79	.88	.32	.42	.52	.69
January 1982	–	–	.28	.75	.34	.56	.31	.62
February 1982	–	–	.04	.42	.47	.81	.30	.78
March 1982	–	–	0	–	.63	.75	.44	.75
April 1982	–	–	.62	.79	.72	.84	.67	.81
May 1982	.57	.94	.64	.81	.61	.88	.61	.87
June 1982	.24	.35	.51	.86	–	–	.25	.52
July 1982	.77	.87	–	–	.78	.93	.59	.90
August 1982	.55	.83	.62	.91	.66	.95	.61	.90
September 1982	.42	.67	.53	.70	.73	.96	.57	.79

The overall contribution of the modification and maintenance actions since January 1, 1982 is shown in Figures 5-62 and 5-63. These show that 35% of the downtime in this period has been caused by the Sta. 360 joint modification and the generator bearing problems. They also show that recurring problems and modifications, for which fixes have been implemented or are being developed, account for over 90% of the downtime.

One factor in the improving availability trend during recent months has been the 24 hour manning of the site. This improves availability by providing rapid response to fault shutdowns. An analysis of the impact of 24 hour manning at the site has shown that if the machines were being operated in a commercial scenario for large clusters with two shift on site coverage, and a two hour response delay on the remaining periods the adjusted availability would decrease approximately 5%. This relatively small contribution of 24 hour coverage, coupled with the improving availability trend in recent months as operating time is built on the machines and the large availability impact of resolvable recurring problems provides confidence that in a commercial scenario the predicted availabilities in excess of 90% can be achieved.

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Item	Hours of downtime	Contribution to lost availability
STA 360 Joint	1047.0	10.1
Generator bearing lube	498.0	4.8
Special tests (TVI, SERI, etc.)	340.0	3.3
LSS bearing seals	82.0	0.8
Quill shaft coupling	59.0	0.6
Engineering instrumentation	154.0	1.5
Actuator seals	48.0	0.5
Rotor weld inspection	161.0	1.6
Control system mods	55.0	0.5
LSS bearing noise	63.0	0.6
Rock anchor checks	91.0	0.9
Yaw drive fasteners	67.0	0.6
Other	289.0	2.8
	2954.0	28.6%

Figure 5-62. Modification Time 1/1/82 - 10/3/82

Item	Hours of downtime	Contribution to lost availability
UPS charging problem	78.0	0.8
Teeter brake	45.5	0.4
Servo valve	18.5	0.2
Slip ring problems	366.0	3.5
IESS valve wiring	20.0	0.2
Vibration sensors	26.0	0.3
Yaw drive bolt torque	23.0	0.3
Air leak in rotor	37.0	0.4
Control system	86.0	0.8
Power instabilities	39.5	0.4
Actuator seals	97.0	0.9
Other recurring problems	170.0	1.6
One-time failures	176.0	1.7
Scheduled maintenance	194.5	1.8
	1377.0	13.3%

Figure 5-63. Maintenance Time 1/1/82 - 10/3/82

5.5.4 Spares

The MOD-2 spares list is shown in Table 5-12. This list has been continuously updated based upon spares usage at the site and modifications to the system configuration. This list is the recommended spares inventory for the three unit cluster. As the system matures and the number of units located in a cluster increases, it can be expected that the quantity of spares required per turbine will decrease.

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Table 5-12. Operational Spares Recommendations (Sheet 1)

FIND NO.	PART NUMBER	MANUFACTURER	DESCRIPTION	QTY	SYSTEM APPLICATION
455200F111	12HMA11511	G.E.	AUXILIARY RELAY	3	BTCU
455200F111	12HMA11C5	G.E.	AUXILIARY RELAY	2	BTCU
455200F111	12ICR51A1A	G.E.	PH. SEQ. & U'VOLT. RELAY	2	BTCU
455200F111	12IJF52A4A	G.E.	OVER/UNDER FREQ. RELAY	2	BTCU
455200F111	16SB1B19	G.E.	CIRCUIT BRKR. CONTROL SWITCH	1	BTCU
455200F111	643X92	G.E.	POTENTIAL TRANSFORMER	2	BTCU
455200F111	700X63G1	G.E.	KILOWATT HOUR METER	1	BTCU
455200F111	852-952A-UVQY	CROMPTON	PHASE SHIFTING XFORMER	2	BTCU
455200F111	8600K92001	G.E.	PHASE SHIFTING XFORMER	1	BTCU
455200F111	9F60FJD040	G.E.	CURRENT LIMITING FUSE	3	BTCU
455200F111	9L11PGB004	G.E.	LIGHTNING ARRESTER	2	BTCU
455200F111	M-0188	BECKWITH	SYNC. CHECK RELAY	2	BTCU
455200F111	M-0193	BECKWITH	SYNCHRONIZING RELAY	1	BTCU
455200F111	SIM TO 700X63G1	G.E.	KILOVAR HOUR METER	1	BTCU
455200F111	6A4260G01	G.E.	THERMOSTAT	2	BTCU/GAJ
455200F111	8421-3	G.E.	FUSE HOLDER, 2-POLE, 250V, 30A	3	BTCU/GAJ
455200F111	AM-4.16-250(KIT)	G.E.	RENEWAL PARTS SET, AIR C.B.	1	BTCU/GAJ
455200F111	AM-4.16-250-9H	G.E.	AIR CIRCUIT BREAKER	1	BTCU/GAJ
455200F111	CAT #9F60BBD001	G.E.	PRIMARY FUSE, PT	4	BTCU/GAJ
455200F111	OT-1801	CHROMALAX	SPACE HEATER	2	BTCU/GAJ
428000F097	1823-1	DWYER INSTR	PRESSURE SWITCH	2	CRACK DETECT
428000F098	1823-10	DWYER INSTR	PRESSURE SWITCH	2	CRACK DETECT
428000F096	289H-41	FISHER CNTL	RELIEF VALVE	2	CRACK DETECT
428000F095	289L-21	FISHER CNTL	RELIEF VALVE	2	CRACK DETECT
428000F093	95007-11	CARGOCAIRE	DEHUMID. AIR FILTER SET	4	CRACK DETECT
430000F038	62813	ELECTROTECH	SLIP RING MODULE-LSS	1	EPS
430000F038	62816	ELECTROTECH	SLIP RING MODULE-LSS	1	EPS
430000F038	62833	ELECTROTECH	SLIP RING B'BLOCK-LSS	1	EPS
430000F038	62844	ELECTROTECH	SLIP RING B'BLOCK-LSS	2	EPS
430000F038	62873	ELECTROTECH	SLIP RING B'BLOCK-LSS	1	EPS
430000F038	62876	ELECTROTECH	SLIP RING B'BLOCK-YAW	1	EPS
430000F038	62879	ELECTROTECH	SLIP RING B'BLOCK-YAW	1	EPS
430000F038	62880	ELECTROTECH	SLIP RING B'BLOCK-YAW	1	EPS
430000F038	63017	ELECTROTECH	SLIP RING B'BLOCK-YAW	3	EPS
454200F066	9T23B3872	G.E.	460V/208V/120V 30KVA XFORMER	1	EPS
454200F067	A11-20-48V-C3	LAMARCHE	BATTERY CHARGER	2	EPS
455200F117	N29T25B5835G6WP	G.E.	4160V/480V 150KVA ACCESS. POWER XFMR	1	EPS
420000F006	8003 3518-A	STAL-LAVAL	SEALING RING	2	G'BOX
430000F154	4-1294	MUNTERS	FILTER ASSEMBLY	6	G'BOX DEHU
420000F006	5911069-4	STAL LAVAL	BULBS	5	G'BOX LUBE
430000F006	595-0258	POWERS	REGULATOR VALVE, NO. 11	1	G'BOX LUBE
430000F006	700-239	POWERS	THERMAL SYSTEM, REG. VALVE	1	G'BOX LUBE
420000F006	8004-1145-1	STAL-LAVAL	TRANSFORMER	1	G'BOX LUBE
420000F006	8004-1146-1	STAL-LAVAL	TEMP. SWITCH	3	G'BOX LUBE
420000F006	8004-1146-2	STAL-LAVAL	TEMP. SWITCH	2	G'BOX LUBE
420000F006	8004-1146-3	STAL-LAVAL	TEMP. SWITCH	1	G'BOX LUBE
420000F006	8004-1147-1	STAL-LAVAL	DIFF. PRESSURE SWITCH	1	G'BOX LUBE
420000F006	8004-1148-1	STAL LAVAL	PRESSURE SWITCH	3	G'BOX LUBE
420000F006	8004-1150-1	STAL-LAVAL	LEVEL SWITCH	1	G'BOX LUBE
420000F006	8004-1166-A	STAL-LAVAL	LOGIC CIRCUIT BOARD	1	G'BOX LUBE
420000F006	8004-2454-1	STAL-LAVAL	PR. RELIEF VALVE	1	G'BOX LUBE
420000F006	8004-2454-1(KIT)	STAL-LAVAL	PRESSURE RELIEF VALVESPRING SET	1	G'BOX LUBE
420000F006	8004-2455-1	STAL-LAVAL	NON-RETURN VALVE	1	G'BOX LUBE
420000F006	8004-2476-1	STAL-LAVAL	CIRCULATION OIL PUMP	1	G'BOX LUBE
420000F006	8004-2477-1	STAL-LAVAL	LUBE OIL PUMP	1	G'BOX LUBE
420000F006	8004-2478-1	STAL-LAVAL	SHAFT COUPLING	2	G'BOX LUBE
420000F006	8004-2479-1	STAL-LAVAL	SHAFT COUPLING	1	G'BOX LUBE
420000F006	8004-2483-1	STAL-LAVAL	LUBE OIL PUMP MOTOR	[illegible]	G'BOX LUBE
420000F006	8004-2484-1	STAL-LAVAL	CIRCULATION OIL PUMP MOTOR	1	G'BOX LUBE
420000F006	8004-2499-1	STAL-LAVAL	ELECTRIC HEATER	2	G'BOX LUBE
420000F006	8004-2509-1	STAL-LAVAL	DIFF. PRESSURE SWITCH	1	G'BOX LUBE
430000F154	8004-9826-1	STAL-LAVAL	DEHUMIDIFIER	1	G'BOX LUBE
420000F006	94/34X500	STAL-LAVAL	FILTER CARTRIDGE-AIR VENT	8	G'BOX LUBE
420000F006	B27	STAL-LAVAL	OVERLOAD RELAY	1	G'BOX LUBE
420000F006	B27-1	STAL-LAVAL	OVERLOAD RELAY	1	G'BOX LUBE
420000F006	GST11-N-25MY	STAL-LAVAL	FILTER CARTRIDGE, LUBE OIL -REUSEABLE	3	G'BOX LUBE
420000F006	IN-AGBR-800/ST11-N-25	STAL-LAVAL	INSERT ASSY, OIL FILTER	1	G'BOX LUBE
420000F006	L.S.-16/L-18G	STAL-LAVAL	CONTACTOR	1	G'BOX LUBE
420000F006	L.S.-20/L-24G	STAL-LAVAL	CONTACTOR	2	G'BOX LUBE
420000F006	L.S.-36/L-44	STAL-LAVAL	CONTACTOR	1	G'BOX LUBE
420000F006	L.S.-6/L-11G11	STAL-LAVAL	CONTACTOR	4	G'BOX LUBE
420000F006	RA-401012	STAL-LAVAL	RELAY	1	G'BOX LUBE
420000F006	RA401615	STAL-LAVAL	RELAY	1	G'BOX LUBE
420000F006	SLFT4952-537	STAL-LAVAL	O-RING, OIL FILTER, VITON 179.3X5.7	12	G'BOX LUBE
420000F006	SLFT4952-543	STAL-LAVAL	O-RING, OIL FILTER, VITON 209.3X5.7	12	G'BOX LUBE
420000F006	T1651-430/T2901-108	STAL-LAVAL	COUPLING BOLT-SET FOR 8004-2490-A	1	G'BOX LUBE

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Table 5-12. Operational Spares Recommendations (Sheet 2)

[illegible]	PART NUMBER	MANUFACTURER	DESCRIPTION	QTY	SYSTEM APPLICATION
[illegible]	[illegible]	OHMITE	RESISTOR	2	GAU
[illegible]	[illegible]	G.E.	LOSS OF EXCITATION RELAY	1	GAU
[illegible]	[illegible]	G.E.	DIFFERENTIAL RELAY	1	GAU
[illegible]	[illegible]	G.E.	LOCK-OUT RELAY (GCB TRIP RELAY)	1	GAU
[illegible]	[illegible]	G.E.	AUXILIARY RELAY	2	GAU
[illegible]	[illegible]	G.E.	OVERCURRENT RELAY	1	GAU
[illegible]	[illegible]	G.E.	OVERVOLTAGE RELAY	1	GAU
[illegible]	[illegible]	G.E.	REVERSE POWER RELAY	1	GAU
[illegible]	[illegible]	G.E.	OVERCURRENT RELAY	2	GAU
453200F000	121RT53C2A	G.E.	TEMPERATURE RELAY	1	GAU
453200F000	165B181	G.E.	C.B. CONTROL SWITCH	2	GAU
[illegible]	[illegible]40[illegible]1AAAB	G.E.	ELAPSED TIME METER	2	GAU
453200F000	643X85	G.E.	POTENTIAL TRANSFORMER	2	GAU
453200F000	6A426G212	G.E.	THERMOSTAT	2	GAU
453200F000	750X1066	G.E.	CURRENT TRANSFORMER	2	GAU
453200F000	750X1068	G.E.	CURRENT TRANSFORMER	3	GAU
453200F000	8411-3	G.E.	FUSE HOLDER, 1-POLE, 250V, 30A	3	GAU
453200F000	9T58B2804	G.E.	TRANSFORMER	2	GAU
453200F000	CR205A002	G.E.	CONTACTOR	2	GAU
453200F000	CR205J002ADA	G.E.	EXCITER FIELD CONTACTOR	2	GAU
453200F000	IC3655A1004	G.E.	POWER FACTOR RELAY	1	GAU
453200F000	R6100425XXZC	WESTINGHOUSE	DIODE	4	GAU
453200F000	R6110425XXZC	WESTINGHOUSE	DIODE	4	GAU
453200F000	SCP250G-60	BASLER	POWER FACTOR-CONTROLLER	2	GAU
453200F000	SR4A3B07B2	BASLER	VOLTAGE REGULATOR	2	GAU
453200F000	XL31K52 1/2 A4-21	S.C.	WATT TRANSDUCER	2	GAU
420000F009	00814237	BELOIT	EXCITER SURGE SUPPRESSOR	2	GENERATOR
420000F009	00856413	BELOIT	BRG. SHELL ASSY. (EXCITER END)	2	GENERATOR
420000F009	00885213	BELOIT	BRG. SHELL ASSY. (DRIVE END)	2	GENERATOR
420000F009	01039635-00814588	BELOIT	EXCITER DIODE (STD. POLARITY)	6	GENERATOR
420000F009	01039636-00814589	BELOIT	EXCITER DIODE (REVERSE POLARITY)	6	GENERATOR
420000F009	CAT #2BSB, TYPE B302	UNITED ELECT	GEN. BRG. OVER/UNDER TEMP. SWITCH	2	GENERATOR
420000F008	07681001	TOLOMATIC	BRAKE LINING SET	2	HSS
421011-001	10923-00	REXNORD	BOLTS-LONG	8	HSS
421011-001	10959	REXNORD	DISC PACK	4	HSS
421011-001	16097-00	REXNORD	BOLTS	24	HSS
420000F008	FS440N	TOLOMATIC	CALIPER ASSY, ROTOR BRAKE	2	HSS
421012-018	032-421012-18	SEAWEST	ROLLER, PRIMARY ENCODER	4	INSTR
411500F011	1308-0063	SPECTROL	POSITION POTENTIOMETER, MODEL 308	2	INSTR
421012F021	70LDIN-2048-0-1-0-A	LITTON	OPTICAL ENCODER, FAILSAFE	1	INSTR
421012F020	70LDIN5000-0-1-0-A	LITTON	OPTICAL ENCODER	1	INSTR
454200F144	800TE14A	ALLEN-BRAD	INTRUSION SWITCH	1	INSTR
411500F026	871FA-122	ROSEMOUNT	ICE DETECTOR SENSOR	2	INSTR
430000F119	9353365	VIBRAMETRICS	VIBRATION SENSOR	1	INSTR
430000F045	W102-P/DC	WEATHERMEAS	WIND SENSOR	2	INSTR
431012F053	1142K13	MCMASTER CAR	SIGHT GAUGE	1	LSS BRGS
421013-1	032-421013-1	CHICAGO RAWH	OIL SEAL	2	LSS BRGS
421013-2	032-421013-2	CHICAGO RAWH	OIL SEAL	2	LSS BRGS
421013-3	032-421013-3	CHICAGO RAWH	OIL SEAL	3	LSS BRGS
421013-4	032-421013-4	CHICAGO RAWH	WEAR SLEEVE	2	LSS BRGS
421013-5	032-421013-5	CHICAGO RAWH	WEAR SLEEVE	2	LSS BRGS
421013-6	032-421013-6	CHICAGO RAWH	WEAR SLEEVE	3	LSS BRGS
431012F070	4450K30	MCMASTER CAR	BREATHER FILTER	2	LSS BRGS
431012F027	5004-35-87	PROTECT CNTL	THERMOSTAT-OPERATIONAL	2	LSS BRGS
431012F046	5004-35-88	PROTECT CNTL	THERMOSTAT-FAILSAFE	2	LSS BRGS
431012F049	FS-GKR-IN	APPLETON ELE	GASKET	2	LSS BRGS
431006-01	2-048-0352	AAA FIRE EXT	CYLINDER W/140# HALON 1301 @ 600 PSI	1	NACELLE
431008-01	2-061-0018	AAA FIRE EXT	SOLENOID PILOT VALVE ASSY - 24 V DC	1	NACELLE
430000F107	2075K16	MCMASTER CAR	FAN-NCU COOLING	2	NACELLE
431008-01	3041-24	JOHNSON CONT	SMOKE DETECTOR, PHOTO ELECTRIC	1	NACELLE
431005F006	600053	WEATHERMEAS	DE-ICING LAMP ASSEMBLY	2	NACELLE
430000F203	77-2008	EG&G	POWER TRANSFORMER (T1)	1	NACELLE
430000F203	77-2013	EG&G	RELAY, SPDT (K2,K3)	1	NACELLE
430000F203	77-2014	EG&G	CAPACITOR (C1)	1	NACELLE
430000F203	77-2040	EG&G	FUSE, FNQ,10 (F2)	5	NACELLE
430000F204	77-2123	EG&G	FLASHTUBE ASSY (V1)	1	NACELLE
430000F204	77-2292	EG&G	SOCKET, FLASHTUBE (SV1)	1	NACELLE
430000F203	77-2365	EG&G	FUSE, 1A, SLO BLO (F1,F5,F6)	5	NACELLE
430000F203	77-2605	EG&G	TIMING & TRIGGER P.C.B. (A1)	1	NACELLE
430000F203	77-2624	EG&G	TRANSFORMER, L.V. LOGIC (T1)	1	NACELLE
430000F201	77-2673	EG&G	SYNC TIMING & DRIVER PCG (A1)	1	NACELLE
430000F203	77-2710	EG&G	RELAY, DPDT (K4)	1	NACELLE
430000F203	77-2732	EG&G	HIGH VOLTAGE MODULE (CR1)	1	NACELLE
430000F203	77-2795	EG&G	CAPACITOR (C2)	1	NACELLE
430000F203	77-2796	EG&G	CAPACITOR (C3)	1	NACELLE
430000F203	77-2797	EG&G	CAPACITOR (C4,C5)	1	NACELLE
430000F203	77-2874	EG&G	FUSE, 1/32A, SLO BLO (F3,F4)	5	NACELLE
430000F203	77-2878	EG&G	RELAY, CONTACTOR (K1)	1	NACELLE
430000F203	77-2928	EG&G	RESISTOR (R2)	1	NACELLE
430000F204	77-2961	EG&G	TRIGGER TRANSFORMER ASSY (T1)	1	NACELLE
430000F201	77-3041	EG&G	RELAY 3PDT (K1,K2,K3,K6,K7)	1	NACELLE

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Table 5-12. Operational Spares Recommendations (Sheet 3)

FIND NO.	PART NUMBER	MANUFACTURER	DESCRIPTION	QTY	SYSTEM APPLICATION
430000F048	CBD-6	AIRSTREAM	RELIEF DAMPER	2	NACELLE
431008-01	DT-200 C	JOHNSON CONT	THERMAL DETECTOR, RATE COMP. 200°	1	NACELLE
430000F100	1LGMODELCRF-18	AIR COMMODIT	EXHAUST FAN	1	NACELLE
430000F047	RESCUMATIC	SAFETY-SUPPL	EMERGENCY ESCAPE DEVICE	1	NACELLE
430000F043	T42B1027	HONEYWELL	THERMOSTAT-FAN	1	NACELLE
457020-1	032-457020-1	BOEING	CIRCUIT CARD ASSY A-2	2	NCU
457022-1	032-457022-1	BOEING	CIRCUIT CARD ASSY A-1	2	NCU
457023-1	032-457023-1	BOEING	CIRCUIT CARD ASSY A-3	2	NCU
457024-1	032-457024-1	BOEING	CIRCUIT CARD ASSY A-6	2	NCU
457025-6	032-457025-6	BOEING	TTL WIRE WRAP BOARD A-4	2	NCU
457011F022	122-105	MOOG	SERVO-AMPLIFIER ASSY	2	NCU
457000F042	10250T112P	CUTLER HAM	PUSH BUTTON ASSY	2	NCU
457013F094	10250T42	CUTLER HAM	CONTACT BLOCK	2	NCU
457013F094	11018-16-3	NATL SEMI	HEADER	2	NCU
457011F051	1N5306	MOTOROLA	DIODE	24	NCU
457013F111	356001	LITTLE FUSE	FUSE BLOCK	3	NCU
457013F113	3AG-312002	LITTLE FUSE	FUSE, 2A	5	NCU
457013F114	3AG-312005	LITTLE FUSE	FUSE, 5A	10	NCU
457013F027	48P5AB15CD	POWER CUBE	POWER SUPPLY #1	2	NCU
457011F015	5031	CODEX CORP	MODEM, ORIGINATE	2	NCU
458000F013	5032	CODEX CORP	MODEM, RECEIVE	2	NCU
457013F032	507-4537-1531-640	AMPEREX/DIAL	LAMP	2	NCU
457000F028	673-1	TELEDYNE	A.C. INPUT MODULE	2	NCU
457000F026	673-21	TELEDYNE	D.C. INPUT MODULE	2	NCU
457000F025	673-22	TELEDYNE	D.C. OUTPUT MODULE	2	NCU
457000F027	673-4	TELEDYNE	A.C. OUTPUT MODULE	2	NCU
457000F021	6A426G001	G.E.	THERMOSTAT-NCU	2	NCU
457013F121	7500K14	CUTLER HAM	SWITCH	4	NCU
457013F086	9274-5569	LEACH	115 VAC RELAY	1	NCU
457013F087	9274-6205	LEACH	28 VDC RELAY	2	NCU
458000F009	95-0408-0933-241	AMPEREX/DIAL	INDICATOR LIGHT	2	NCU
457013F112	AGC-1	BUSSMAN	FUSE, 1A	15	NCU
457013F088	CDC-38-30025	POTTER BRUM	24 VDC RELAY	1	NCU
457013F089	CDC-38-30030	POTTER BRUM	24 VDC RELAY	1	NCU
457013F095	DH0008CN	NATL SEMI	DIGITAL DRIVER	2	NCU
457000F023	FS2051	G.E.	HEATER STRIP	2	NCU
457013F015	JA-A3-A15-2	HEINEMANN	CIRCUIT BREAKER	2	NCU
457013F016	JA1-A3-A-20-2	HEINEMANN	CIRCUIT BREAKER	2	NCU
457013F017	JA1-G3-A-10-2	HEINEMANN	CIRCUIT BREAKER	2	NCU
457013F090	KRP 14 DG-24V	POTTER BRUM	24 VDC RELAY	3	NCU
457013F028	LCD-2-22	LAMBDA	POWER SUPPLY #2	2	NCU
457000F116	LGS-5-28D-OV-4	LAMBDA	POWER SUPPLY, 28VDC (F/S)	2	NCU
457000F115	LGS-5-5D-OV-R	LAMBDA	POWER SUPPLY #4	2	NCU
457000F114	LM-228-Y	LAMBDA	POWER SUPPLY - 28VDC-#3	2	NCU
457011F014	MTA-406N-WW	ALCO ELECTR	SWITCH	2	NCU
457013F008	TDP-1	HI-G CO.	RELAY	2	NCU
457011F042	V18ZA1	G.E.	VARISTOR	2	NCU
457010F024	Z80-A10	ZILOG	ANALOG BOARD ASSY A-7	2	NCU
455200F112	CAT #1-30K	QUALITROL	GAGE, LIQUID LEVEL	1	OUTPUT XFMR
455200F112	CAT #11082-2 R.3 GR2 PT1	UPTEGRAFF	BUSHING ASSY. LOW VOLTAGE	3	OUTPUT XFMR
455200F112	CAT #11082-5 R.3 GR2 PT1	UPTEGRAFF	BUSHING ASSY. HIGH VOLTAGE	4	OUTPUT XFMR
455200F112	CAT #152115-200, TYPE B	KEARNEY	FUSE, AIR INTERRUPT SW.	6	OUTPUT XFMR
455200F112	CAT #1925-29	ROCHESTER	THERMOMETER	1	OUTPUT XFMR
455200F112	CAT #70-35C	QUALITROL	PRESSURE VACUUM GAUGE SET	1	OUTPUT XFMR
455200F112	TYPE EJ1 #9F60BHH905	G.E.	PRIMARY FUSE, PT SIZE B	2	OUTPUT XFMR
455200F112	TYPE JKS-5 639X90	G.E.	CURRENT TRANSFORMER	2	OUTPUT XFMR
455200F112	TYPE JVM-5, "685X46	G.E.	POTENTIAL TRANSFORMER FUSED	2	OUTPUT XFMR
428002F051	01907	DELAVAL TURB	LOW LEVEL SWITCH-HYD RESERVOIR	2	PITCH CNTL
418003-1	032-418003-1	REED INSTR	HYDRAULIC SWIVEL/ACTUATOR ASSY	1	PITCH CNTL
418004-13	032-418004-13	RENTON COIL	SPRING, TIP LOCK	2	PITCH CNTL
428006F046	1/2 DISC (7101501)	FIKE METAL	RUPTURE DISC, 600 PSI	6	PITCH CNTL
428006F029	1/2-30SB	FIKE METAL	RUPTURE UNIT (HOUSING)	1	PITCH CNTL
418004-014	1 1/2HHSL0.82-AK	SHEFFER	ACTUATOR	1	PITCH CNTL
428006F034	19R3-D4-C1A	SOR INC.	PRESSURE SWITCH, RETURN LINE	2	PITCH CNTL
428000F108	1K-01204-01	DOUBLE-A	MANIFOLD SEAL KIT	1	PITCH CNTL
428000F137	206K	FAFNIR	BEARING-HYD RESERVOIR	2	PITCH CNTL
428000F137	208129C	DELAVAL BARK	THERMOWELL	2	PITCH CNTL
428002F045	208K	FAFNIR	BEARING-HYD RESERVOIR	2	PITCH CNTL
428006F047	283064-0001	MAROTTA	SOLENOID VALVE, IESS	4	PITCH CNTL
428006F012	283065-0001	MAROTTA	SOLENOID VALVE, START-STOP	2	PITCH CNTL
428000F181	3-8N552-90	PARKER-HANN	"O" RING FOR 5159T RELIEF VALVE	6	PITCH CNTL
428000F114	31P10BE50YMYM-1	PARKER-HANN	FILTER ASSY, HYDR SUPPLY	2	PITCH CNTL
418002F004	3D03-33-003-06-03-0085	ABEX-DENISON	DIRECTIONAL VALVE	1	PITCH CNTL
418002F006	3D03-33-003-11-03-0-0-B	ABEX-DENISON	DIRECTIONAL VALVE	1	PITCH CNTL
428000F104	458-12S-26	TELEDYNE	CHECK VALVE	2	PITCH CNTL
428000F103	458-8S-26	TELEDYNE REP	CHECK VALVE	2	PITCH CNTL
418000F061	50-16	DRAGON	DRAGON HAND VALVE	3	PITCH CNTL
428000F101	5008	DRAGON	VALVE-NEEDLE	2	PITCH CNTL

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Table 5-12. Operational Spares Recommendations (Sheet 4)

FIND NO.	PART NUMBER	MANUFACTURER	DESCRIPTION	QTY	SYSTEM APPLICATION
428000F073	505-2-3-F	O&M SPECIALT	PRESSURE SNUBBER	2	PITCH CNTL
428000F107	6159T-8TB-75	CIRCLE SEAL	RELIEF VALVE	2	PITCH CNTL
428002F041	57XL-40	LENZ	FILLER CAP ASSY-HYD RESERVOIR	2	PITCH CNTL
428000F079	6607A-7-91	CCC	PR. SWITCH, 430 PSI	3	PITCH CNTL
428000F078	6607A-8-65	CCC	PR. SWITCH, 1500 PSI	3	PITCH CNTL
428000F080	6607A-8-66	CCC	PRESSURE SWITCH, 1900 PSI	1	PITCH CNTL
428000F110	666025K000	PARKER-HANN	ACCUMULATOR SPARES KIT	2	PITCH CNTL
430000F042	709-CAD	ALLEN-BRAD	MOTOR STARTER	1	PITCH CNTL
428000F033	72CF10CEC15Y0Y0-1	PARKER-HANN	FILTER ASSY, HYDR RETURN	2	PITCH CNTL
418004-014	760-01-0150-0062	SHEFFER	PACKING KIT, TIP ACTUATOR	1	PITCH CNTL
418002F008	77093	ABEX-DENISON	SERVO VALVE	2	PITCH CNTL
428002F042	8280	ROCHESTER	GAUGE-HYD. RESERVOIR, 16.0 LG.	1	PITCH CNTL
428000F033	908648	PARKER-HANN	ELEMENT FOR 72CF FILTER (RETURN)	6	PITCH CNTL
428000F114	983061	PARKER-HAN	ELEMENT FOR 31P FILTER (SUPPLY)	3	PITCH CNTL
428000F091	9T58B1813	G.E.	TRANSFORMER	1	PITCH CNTL
428000F108	AQP-06-10A1	DOUBLE A	CHECK VALVE-PILOT	2	PITCH CNTL
428002F043	CAY 94-3	AIRFLYTE ELE	BRUSH BLOCK-HYD RESERVOIR	2	PITCH CNTL
418003F002	CB502A-HLU1	PARKER-HANN	BODY SEAL KIT, PITCH ACTUATOR	2	PITCH CNTL
418002F007	CS 800S	PARKER-HANN	CHECK VALVE	2	PITCH CNTL
428000F105	D1VW20B4DY	PARKER-HANN	SOLENOID VALVE	2	PITCH CNTL
428000F116	DD-1101-47	REULAND	ELECTRIC MOTOR	1	PITCH CNTL
428002F046	F-SD-3020-A-DD-1.625	CRANE PACK	FACE SEAL-HYD RESERVOIR	1	PITCH CNTL
418003F006	HT40-101	NMB CORP	SPHERICAL BEARING	2	PITCH CNTL
418003F002	L06942-0000	PARKER-HANN	PISTON RINGS KIT, PITCH ACTUATOR	2	PITCH CNTL
418002F005	MHC20-T40A-4	SNAP-TITE	OVERCENTER VALVE	2	PITCH CNTL
428000F127	MT1H-H251S	DELAVAL	TEMPERATURE SWITCH	2	PITCH CNTL
428000F126	P9201	CONTROL PROD	TEMPERATURE SWITCH	2	PITCH CNTL
428000F115	PV06-007-51L-04	DENISON	HYDRAULIC PUMP	1	PITCH CNTL
418000F102	RDV22-T8140A	SNAPTITE	RELIEF VALVE	2	PITCH CNTL
418003F002	RG2AHL-0355	PARKER-HANN	GLAND CARTRIDGE KIT	2	PITCH CNTL
428000F115	S15-15239	ABEX-DENISON	PUMP SPARES KIT	1	PITCH CNTL
418002F003	TPCCSL600SAL8	PARKER-HANN	FLOW CONTROL VALVE	2	PITCH CNTL
411306-1	032-411306-1	SERVICE BRON	BUSHING	2	ROTOR
411306-2	032-411306-2	SERVICE BRON	BUSHING	2	ROTOR
411306-3	032-411306-3	SERVICE BRON	BUSHING	2	ROTOR
411307-1	032-411307-1	KEY BELLEVIL	BELLEVILLE SPRING	2	ROTOR
418000F033	23000012-0544J	TITEFLEX	HOSE ASSY-TEFLON	6	ROTOR
418000F034	8010606-12-12-55	PARKER-HANN	HOSE ASSY-RUBBER	4	ROTOR
411311F031	HH 840210	TIMKEN	BEARING CUP	2	ROTOR
411311F030	HH 840249	TIMKEN	BEARING CONE	2	ROTOR
411311F036	JM 15015-LPD(H5L16)	J.M. OIL SLS	OIL SEAL, INBD-INT.	2	ROTOR
411311-02	JM 18858	J.M. OIL SLS	OIL SEAL, OUTBD-EXT.	3	ROTOR
411311F034	JM 6334-LUP(H5L16)	J.M. OIL SLS	OIL SEAL,OUTBD-INT.	3	ROTOR
411311F035	JM 9833-OLL-PD(H1/L5)	J.M. OIL SLS	OIL SEAL, INBO-EXT.	3	ROTOR
411311F033	LM 565910	TIMKEN	BEARING CUP	3	ROTOR
411311F032	LM 565949	TIMKEN	BEARING CONE	2	ROTOR
413000F031	032-413003-5	SEAWEST	BUMPER ASSY	2	ROTOR
413000F031	9680106	GOODYEAR	SEAL	2	TEETER
413000F031	9680107	GOODYEAR	BACK-UP RING	3	TEETER
413000F031	9684796	GOODYEAR	BACK-UP RING	3	TEETER
413000F031	9685214	GOODYEAR	SEAL	3	TEETER
413000F031	39640155	GOODYEAR	BRAKE LINING SET	3	TEETER
413000F031	9650236	GOODYEAR	BRAKE CALIPER ASSY	8	TEETER/YAW
435000F014	112-1017	EATON/CHARLY	HYD DRIVE MOTOR	4	TEETER/YAW
435000F014	14253	EATON	BOLT, RETAINER	1	YAW CONTROL
430000F147	2122A9SJ	CONTROL PROD	TIME DELAY RELAY, ROTOR BRAKE	6	YAW CONTROL
435000F013	39630906	GOODYEAR	BRAKE LINING SET	1	YAW CONTROL
435000F014	61104	EATON	SEAL KIT, SHAFT	3	YAW CONTROL
435000F014	61105	EATON	SEAL KIT, MOTOR, REAR	1	YAW CONTROL
435000F014	61108	EATON	SHAFT AND BEARING KIT	1	YAW CONTROL
435000F015	620	GEAR WORKS	PLANETARY SPEED REDUCER	1	YAW CONTROL
435000F013	9640152	GOODYEAR	BRAKE CALIPER-DRAG	1	YAW CONTROL
435000F051	PCCM600S	PARKER-HANN	FLOW CONTROL VALVE	1	YAW CONTROL
435004F013	10HP-1800RPM	REULAND	MOTOR-ELECTRIC	2	YAW CONTROL
435004F133	2495-2PP	CIRCLE SEAL	VALVE-CHECK, ROTOR BRAKE PRESS.	1	YAW HPU
435004F016	53576	PUROLATOR	FILTER, SUPPLY	2	YAW HPU
435004F020	6607A-7-85	CCC	PR. SWITCH N/O TO CLOSE AT 500 PSI	1	YAW HPU
435004F142	6607A-8-72	CCC	PRESS. SWITCH, 1600PSI	2	YAW HPU
435004F022	6607A-9-59	CCC	PR. SWITCH N/C TO CLOSE AT 2000 PSI	1	YAW HPU
435004F102	709808103	ALLEN BRAD	MAGNETIC STARTER	2	YAW HPU
435004F016	7515130	PUROLATOR	ELEMENT FOR 53576 FILTER (SUPPLY)	1	YAW HPU
435006F010	920523	PARKER-HANN	ELEMENT FOR F331RF FILTER (RETURN)	3	YAW HPU
435004F029	BNNNC-005-L(1)	DOUBLE A	VALVE-RELIEF	2	YAW HPU
435004F015	C1200SY	PARKER-HANN	VALVE-CHECK	2	YAW HPU
435004F031	D1VW20BYV	PARKER-HANN	DIRECTION VALVE, YAW BRAKE	2	YAW HPU
435004F030	D1VW4CYY	PARKER-HANN	DIRECTIONAL VALVE, HYD. MOTOR	2	YAW HPU
435004F018	H2082	MARSH	PRESSURE GAUGE	2	YAW HPU
435006F011	IE2D5	ITT-VULCAN	THERMOSTAT, HEAT EXCHANGER	1	YAW HPU
				2	YAW HPU

6.0 CONCLUSIONS AND RECOMMENDATIONS

The MOD-2 project has been successfully concluded after a five year effort by BEC and its subcontractors, under the contractual direction of NASA Lewis Research Center for DOE. The project has developed a wind turbine design meeting the contractual design requirements and has fabricated and tested three machines of this design, which have demonstrated fulfillment of the project goals. These machines will continue the demonstration as remotely controlled power generators within the Bonneville Power Administration network. The project has produced considerable valuable technical data needed to bring large wind turbine systems to commercial status and contributing to the nation's energy production.

The major system accomplishments demonstrated at Goodnoe Hills are as follows:

(1) The feasibility of fabrication and installation of a multi-megawatt (2.5 MW) horizontal axis machine with a 300 foot diameter rotor. The MOD-2 rotor is the largest rotor fabricated and tested to date, and the MOD-2 has produced higher power output than any other wind turbine system to date.

(2) Unattended operation with remote monitoring, enable/disable control and energy management capability.

(3) Power variations of less than ±6 percent (50 percentile data) for power delivered to the utility grid. Three sigma values are within ±18 percent at the maximum wind speed of 45 mph.

(4) The feasibility of the controlled yaw upwind rotor, which has more efficient energy capture than a downwind rotor, and which has demonstrated fully acceptable noise characteristics.

(5) The feasibility of the partial span (30%) tip controlled rotor.

(6) The adequacy of the failsafe shutdown system protection.

(7) Evaluation of early prototype operations have shown that the machines are achieving an availability of 0.83 for those periods when system design modifications or special tests are not included as period time in the calculation. Projections indicate a capability to achieve greater than 0.92 as early operational problems are solved.

Testing of the MOD-2 units at Goldendale has verified many unique design features of the MOD-2 and is providing invaluable technical data on loads and control system dynamics. Major areas of technical interest where the data will contribute to future development and commercialization include:

(1) The large-scale elastomeric teeter bearings successfully completed accelerated life-cycle laboratory testing and have exhibited no problems during operation.

(2) Actual teeter motions are less than had been expected. No teeter stop contacts have been observed during rotation. The teeter brakes appear to be unnecessary and have been deactivated which will improve overall reliability.

(3) The yaw damping brake has proven to be unnecessary and has been deactivated which will improve overall reliability.

(4) The measured yaw drive cyclic loads are higher than predicted. These loads can be reduced by sizing the drive motor to stall and allowing backdriving during peaks in the cyclic loads.

(5) Structural rotor loads prediction methods were verified for all loading conditions except for rotor flapwise cyclic loads which are higher than predicted by analysis methods. Prediction methods have been modified to reflect this inadequacy and can be used with confidence to predict cyclic rotor loads of other machines. Control system interactions are being evaluated and current control system testing is expected to provide some alleviation of cyclic loads.

(6) The compliant quill shaft, in conjunction with the pitch control system, has demonstrated the capability of damping power oscillations from rotor to gearbox. The three sigma cyclic torque loads are 50 percent of the predicted design loads.

(7) A system simulation model has been developed and correlation with actual system dynamics is providing the capability to optimize the control system for loads reduction and power stability while achieving maximum energy output.

(8) Measurements of actual power output versus meteorological tower wind speeds show good correlation with predicted values. The data are based on 10 minute averages (at a data rate of 10 samples per second) during selected periods of relatively steady winds. Approximately one-third of the data points are higher than predicted values. Two thirds of the data points are less than predicted values. The maximum data scatter of approximately 20% can be attributed to windspeed at the turbines being different than wind speed at the meterological tower, losses due to yaw error, and accuracy of the data systems.

In summary, the MOD-2 project goals have been achieved. A wide base of suppliers involvement has contributed to the program. Utilities have participated in the design and evaluation. The three MOD-2 machines at Goldendale, plus a MOD-2 machine at Medicine Bow, Wyoming, operated by the Bureau of Reclamation and a MOD-2 machine at Solano, California, operated by Pacific Gas and Electric are contributing to the data base. The feasibility of the large machines has been demonstrated and provide the technical confidence for development of even larger next-generation machines. Continued operation will demonstrate the economic viability of wind energy systems operated to save expendable and costly fossil fueled generating systems.

The existing three units at Goldendale provide an excellent test facility for continued industry evaluation and development of advanced systems. This facility is continuing in a test mode under the program direction of NASA/BPA. Specific areas of continued evaluation and test should include:

(1) Control system/performance optimization with continued development of analytical modeling including wind turbulence induced effects.

(2) A continued operational evaluation of performance, component reliability, maintenance timelines, and system availability to provide the utility industry with a firm basis for economic evaluation.

(3) A product improvement program to correct any potential design deficiencies impacting system availability, maintenance procedures or personnel and equipment safety.

(4) Long term evaluation of environmental impacts.

(5) Cluster array analysis with testing for wake effects.

(6) Advanced concepts verification including new materials, airfoil shapes, tip speed effects, etc.

APPENDIX A
SITE DEVELOPMENT AND WTS ERECTION

The construction of three MOD-2 wind turbine systems at Goodnoe Hills, WA. required completion of the following major tasks: 1) Constructing foundations, 2) Erecting a gin pole for hoisting the wind turbine components, 3) Erecting the tower, 4) Installing the nacelle on the tower, 5) Installing the rotor on the low speed shaft, and 6) Installing the electrical equipment required to transmit the power from the wind turbine generator to the Bonneville Power Administration substation. Bonneville Power Administration provided the wind turbine site locations, the roads to the sites, temporary construction power, and the substation to interface the three wind turbines with the electrical power grid.

The construction process began at site #1 with construction of ten foundations requiring a total of approximately 710 cubic yards of concrete. (Seven gin pole foundations, one tower foundation, one electrical equipment pad, and one maintenance equipment foundation). The construction process for all foundations was similar. After a hole was excavated to the proper dimensions, wooden forms were constructed and the specified rebar, anchor bolts, conduits and embeds were placed within the forms. Concrete was then placed in the forms and allowed to cure. The forms were then removed and backfill placed around the foundations.

The tower foundation required installing rock anchors in addition to the rebar and tower anchor bolts. Following excavation for the tower foundation, seventy-two holes were drilled into the rock and rock anchors twenty-eight feet in length were installed. The rock anchors were centered in the holes, and secured by grout pumped in the holes and allowed to cure. Figure A-1 shows the rock anchors installed in the foundation excavation. Following the installation of the rock anchors, construction of the tower foundation continued with the installation of forms. After the tower foundation was poured and cured the rock anchors were tensioned to approximately 154,000 pounds. Figure A-2 shows the completed foundation installation.

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Figure A-1. Rock Anchor Installation

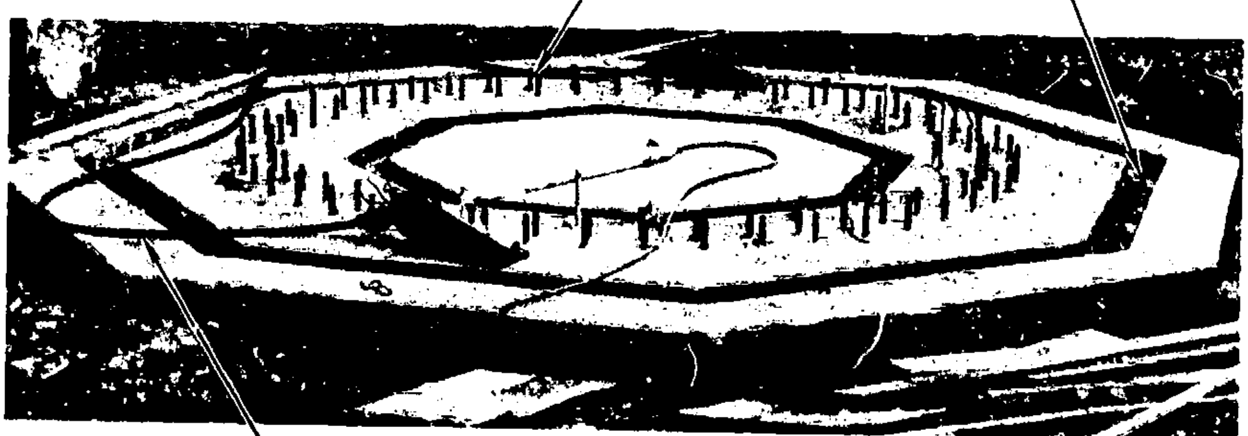

Figure A-2. Completed Foundation

Following the completion of the foundations the gin pole was erected to hoist the heavy components of the wind turbine. The 250' gin pole was assembled and partially rigged on the ground and lifted onto the boom rest tower using a crane. After rigging of the gin pole was complete it could lift itself into working position by pulling against the boom-up pendant which was attached to the tower foundation (Figure A-2). The gin pole was load tested by lifting six culverts filled with concrete weighing a total of 213,000 pounds.

The tower was erected by welding factory fabricated segments in place on the tower foundation. First, two base sections with the base plate and gussets factory welded were placed over the ninety-six anchor bolts and leveled with shim packs. The base sections were then welded together. Four petal sections were then welded on top of the completed base section. Four smaller petals were then welded together beside the tower, lifted into place and welded to the previously completed structure. This completed the conical section of the tower. A forty foot cylindrical section with the hyperbolic transition attached was then welded onto the conical section (Figure A-3). Three more forty foot cylindrical sections were then welded on the preceeding sections to bring the tower to its completed hieght of 196 feet. Figure A-3 shows the last tower section being placed. All sections were welded from temporary scaffolding tack welded to the tower structure. Each section was checked for plumbness as it was added. Following the welding of the basic structure the catwalk was welded at the top of the tower and a door was cut in the base of the tower and reinforced. Grout was then placed under the base plate and the anchor bolts tensioned. After the tower erection was complete the tower was sand blasted and three coats of epoxy paint applied. The tower for Unit one was erected using the gin pole. A conventional crane was used to erect the towers for Units two and three as the gin pole was in use at site #1.

Due primarily to transportation limitations, the nacelle and contents was received at the construction site partially assembled. It was off-loaded onto stands and fully assembled on the ground prior to installation on the top of the tower. Figure A-4 shows the nacelle resting on its stands at the tower base. The nacelle was equipped with removable hatches to facilitate the

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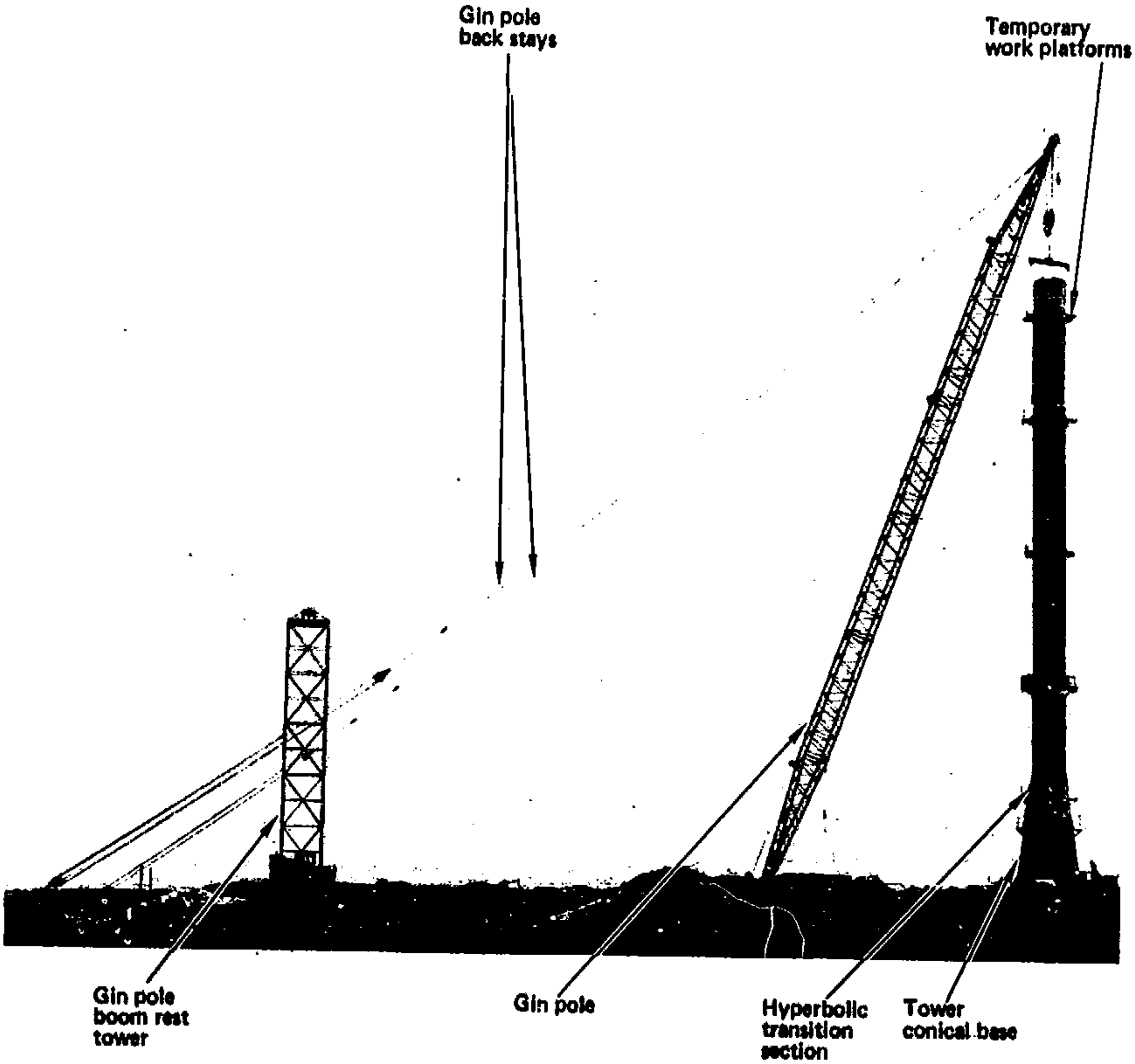

Figure A-3. Tower Installation

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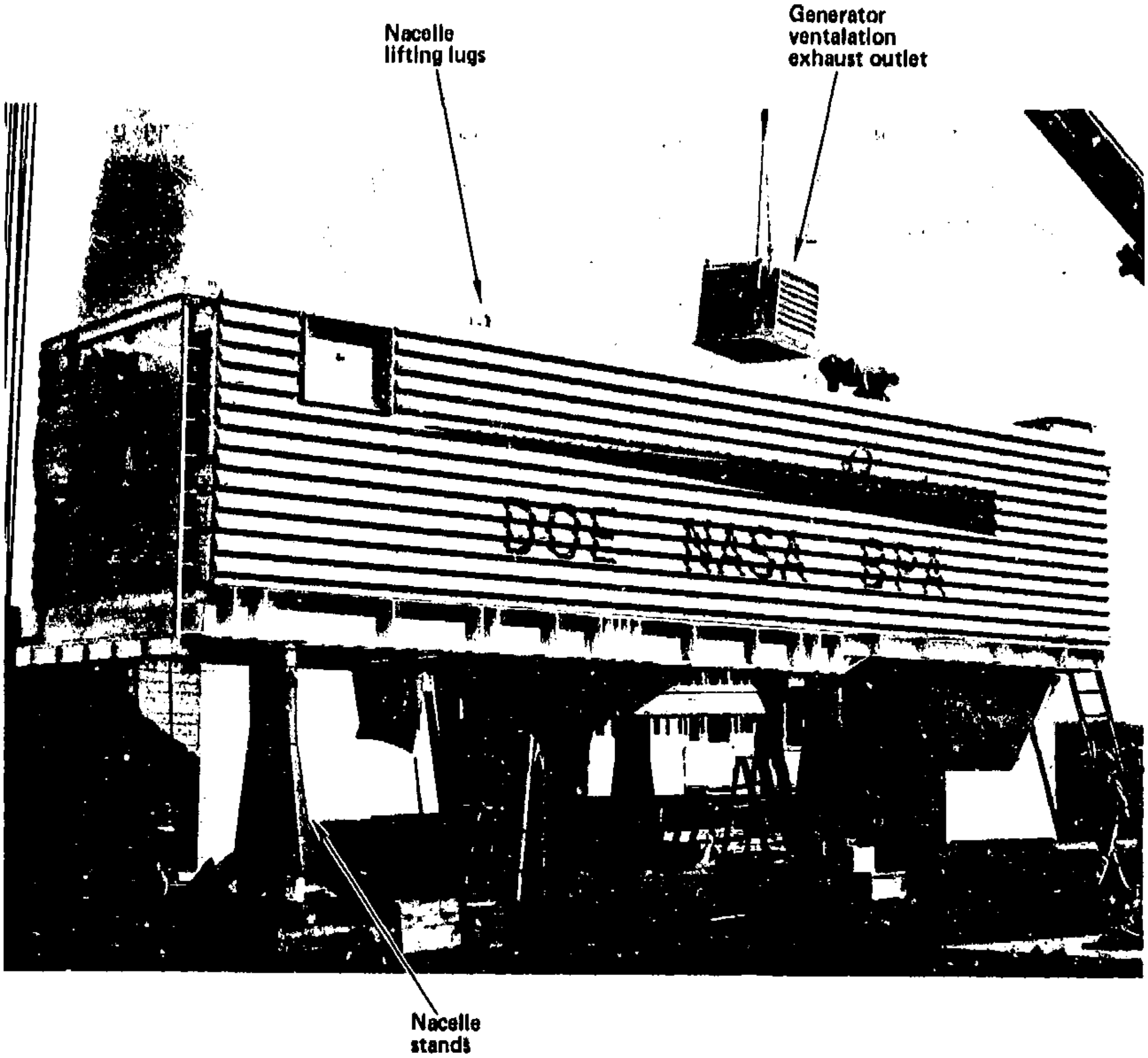

Figure A-4. Nacelle Assembly at Site

installation of internal equipment. The quill shaft coupling, the gearbox and the generator were placed in the nacelle through these hatches. The hatches were replaced and the gearbox oil cooler, the wind sensors, the ventilators, and the aircraft warning lights were installed on the nacelle roof. The yaw bearing, the yaw brakes, the yaw brake disk and the gearbox oil reservoir were bolted beneath the nacelle. Piping was installed to connect the gearbox with the various components of the lubrication system. Following flushing of the lubrication system, leak testing and completion of electrical installation work, the Nacelle Integration Test was completed to ensure proper operation prior to installation on top of the tower.

In preparation for hoisting the nacelle four tag lines were attached to the corners of the nacelle and secured to winches mounted on heavy equipment. These lines were used to stabilize the nacelle during the lift and to align the nacelle as it was set on the top of the tower. A lifting fixture designed for the nacelle lift and previously load tested to 200% of the nacelle weight was pinned to lifting lugs on the nacelle roof (Figure A-4). The nacelle was then hoisted to the top of the tower and bolted in place (Figure A-5). The tag lines were removed, the wind sensors raised and the nacelle was yawed to face the gin pole in preparation of the rotor lift.

The rotor was received in five sections for Unit one, (one hub, two mid-sections and two tips). The hub was off-loaded, rolled onto edge with a handling fixture and placed in holding fixtures. The mid-sections were bolted to the hub and the joint sealed. The tips were joined to the mid by inserting the spindle in the mid and bolting the spindle barrel and actuator swivel to the mid-sections. For Units two and three the mid-blade was shipped with the tip attached to reduce field installation costs. Figure A-6 shows a mid-tip assembly arriving at the site. After the rotor was assembled it was balanced by placing a specified amount of weight in one of the mid-sections. The rotor integration test was then completed to verify the integrity of the rotor hydraulic and electrical systems and to verify the rotor was sealed for proper operation of the crack detection system prior to installing it on the turbine.

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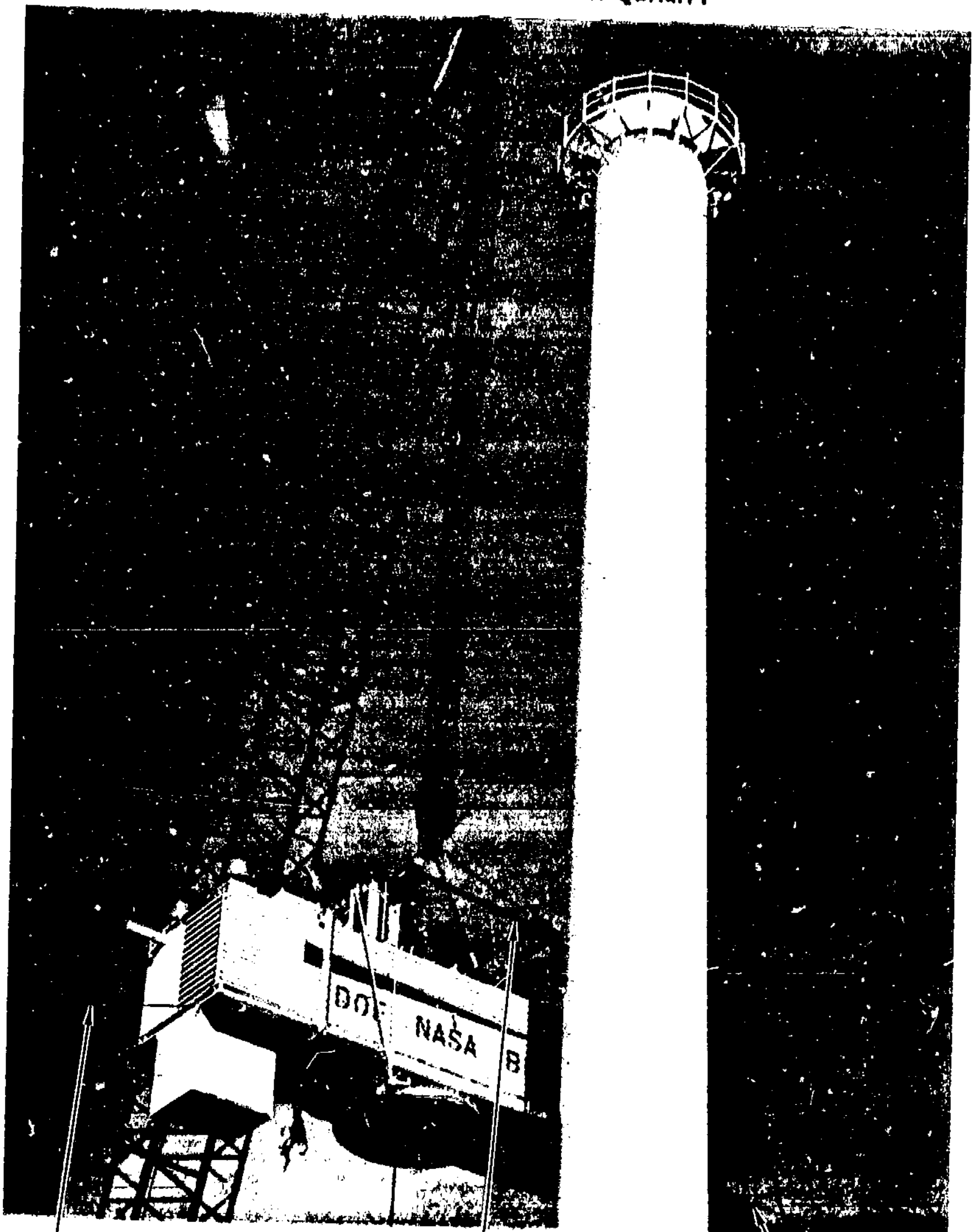

Figure A-5. Nacelle Installation

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Figure A-6. Mid-Blade, Tip Transportation

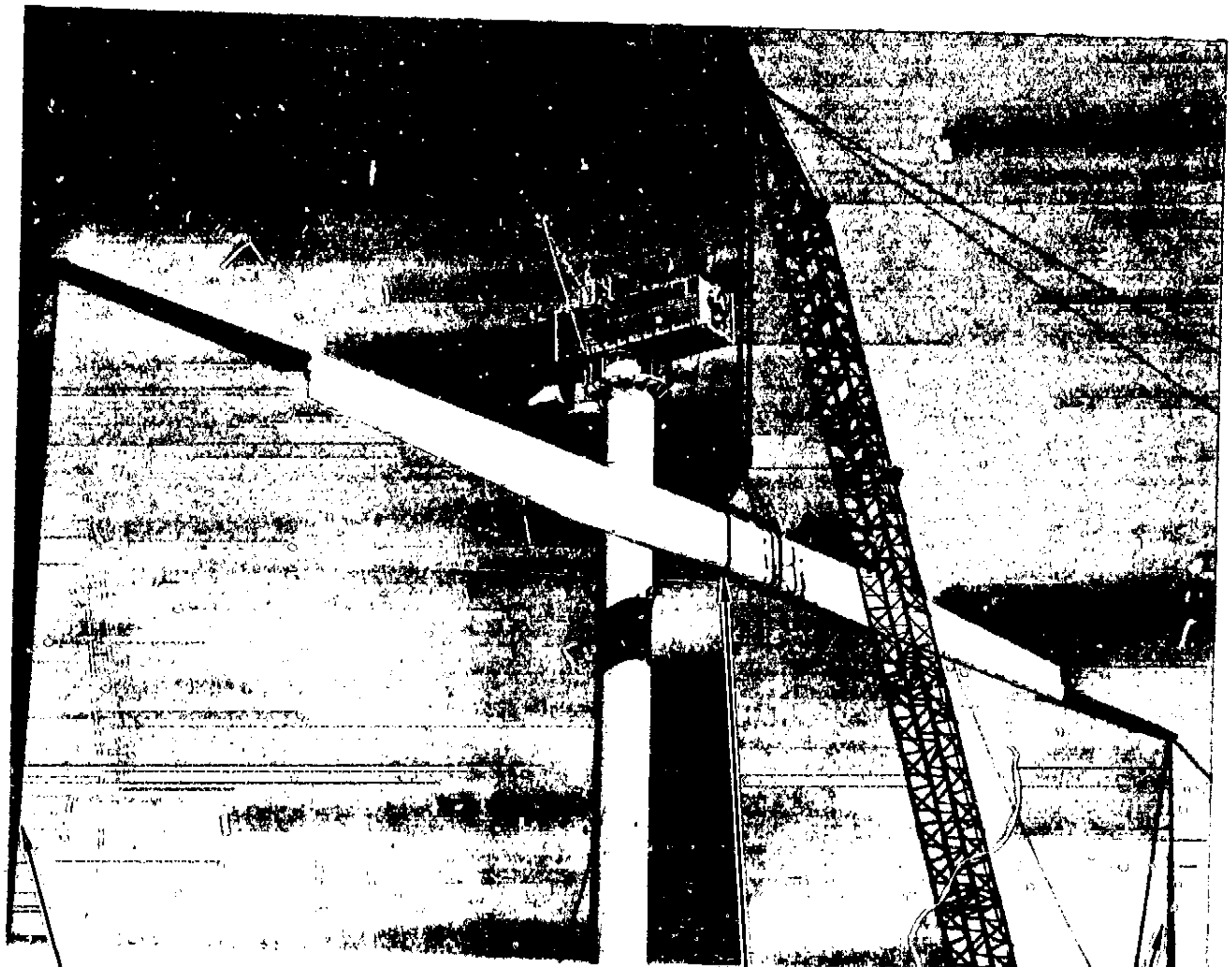

Figure A-7. Rotor Installation

To provide stability during the rotor lift the same four part tethering system used on the nacelle lift was attached to the ends of the rotor. A lifting fixture designed for the rotor lift and previously load tested to 200% of the rotor weight was attached to the rotor and the rotor was hoisted into place (Figure A-7). The rotor was then bolted to the low speed shaft and the hydraulics and electrical connections made. The rotor remained tethered to prevent its rotation during drive train alignment.

Following drive train alignment the rotor was rotated to a vertical position using the rotor positioning tool to allow installation of the teeter stops. Installation of the teeter stops completed the WTS structural assembly.

During the construction process electrical equipment was being installed throughout the wind turbine system. This included installation of the yaw slip ring, cable trays, wiring, electrical switchgear and transformers, buried cable to the B.P.A. substation and fiberoptics to the data center.

Following completion of Unit one, the gin pole was moved to Units two and three for installation of the nacelle and rotor on those units. Construction of Units two and three was similar to the process described for Unit one with the exceptions previously discussed.

APPENDIX B

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOL	MEANING
a	power scaling exponent
a	windage churning loss
a	length
A	amplitude of gusts
AEP	annual energy production
AH	amphere hours
AISC	American Institute of Steel Construction
Alt	altitude
Ap	particular value of "A"
AOM	annual operations and maintenance costs
b	width
BEC	Boeing Engineering and Construction
BFL	basic factory labor
BTU	British thermal unit(s)
c	chord (airfoil)
c	Weibull constant
c.g.	center of gravity
C_D (C_d)	drag coefficient
C_L (C_l)	lift coefficient
COE	cost of electricity
COEP	cost of electricity program
C_p	power coefficient
C.P.G.	compact planetary gear

CPM (CP_m)	maximum system efficiency
CP_{max}	maximum rotor power coefficient
C_r	critical buckling stress
CRT	computer remote terminal
Cu	copper
cu. ft.	cubic feet
C.Y.	cubic yards
D (DIA)	diameter
da/dn	crack growth rate
db	decibal (s)
DC	direct current
DG	diesel driven generator
DOE	Department of Energy
E	modulus of elasticity
EOCP	energy output computer program
E_s	specific energy
f	limit load stress
F_{cr}	critical load
FCR	fixed charge rate (annualized)
FMAT	material factor
FMEA	failure mode and effects analysis
FMFG	manufacturing factor
f_n	frequency requirement
F (P)	load
FPS	feet per second
FR	failures per year

freq.	frequency
ft.	feet
$ft.^2$	square foot
g	acceleration due to gravity
G	modulus of rigidity
GCB	generator circuit breaker
GR	steel grade
hr(s)	hour(s)
Hz (HZ)	Hertz (cycles/sec.)
IC	total WTS cost
in (s)	inch (es)
K	Weibull constant (exponent)
K	one thousand
K_c	buckling constant
K_{max}	maximum stress intensity for each block of cycles
K01	maximum stress intensity on each spectrum
KPC	pitch control cost factor
KRO	baseline value (cost)
Ksi	thousand pounds per square inch
KV	kilovolt (s)
KVA	kilovolt amphere (s)
kW	kilowatt (s)
kWh	kilowatt hour (s)
Kips	thousand pound (s)
lb(s) (#)	pound (s)
L.E.	leading edge
LERC (LRC)	Lewis Research Center

m	meters
M	moment
max	maximum
MDT	mean down time
min	minimum
mph	miles per hour
M.S.	margin of safety
MSB	most significant bit
MTBF	mean time between failure
MW	megawatt (s)
MWh	megawatt hour (s)
n	number of spares
n	circular frequency
N	efficiency
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautic and Space Administration
O & M	operations and maintenance
O.D.	outside diameter
PF	power factor
P_s	specific power
psi	pounds per square inch
Powgn	power error gain
PT	particle test method
r	radial distance from hub center
R	radius of WTS rotor
R	minimum stress/maximum stress

RAD	radian (s)
RAM	Reliability, Availability, Maintainability
rev	revolution
ROT	rotor cost
rpm	revolutions per minute
RT	radiographic test method
RTGN	rate error gain
s	stress
s (sec)	second (s)
SCF	structural composites industries
STD	standard temperature day
t	thickness
t	recorder time
T.E.	trailing edge
T_W	torque extracted from wind
UPS	uninterruptable power supply
UT	ultrasonic test method
v	volt (s)
V (V_W)	wind velocity
V_r	rated wind velocity
Vel	velocity
V_{in}	cutin wind velocity
V_o	design wind velocity
Vo	emprical homogenous wind speed
V_{out}	cutout wind velocity
V_r	reference wind velocity
VT	visual test method

WT	weight
WT	wind turbine
WTS	wind turbine system
x	reference axis
y	reference axis
yr	year (s)
z	reference axis
z	elevation above ground level
z_o	surface roughness length
z_r	reference height
'	feet
"	inches
¢	cents
$	dollars
%	percent
$^\circ$F	temperature, Fahrenheit
$^\circ$C	temperature, Centigrade
$F	cost of failure
$^\circ$	degrees
$<$	less than
$\leq$	less than or equal to
$=$	equal to
$>$	greater than
$\geq$	greater than or equal to

<<<	much less than
>>>	much greater than
λ	failure rate
σ	solidity
ϕ	phase (electrical)
ϕ ($\emptyset$)	wind yaw error
σ	standard deviation
θ_C	collective pitch angle
ϕ_x	longitudinal component of turbulence spectrum
σ_x	longitudinal turbulence intensity
Δ	wind velocity separation distance
ρ	air density
$\dot{\theta}$	rotor rate
Δ	change
ρ	density
μ	Poisan's Ratio
θ	pitch angle
η	efficiency

APPENDIX C

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5. DOE CONF-810752/NASA CP2230, Large Horizontal Axis Wind Turbines, "Development Tests for MOD-2 Wind Turbines," July 28-30, 1981.